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An Exploratory Data Analysis Approach for Land Use- Transportation Interaction: The Design and Implementation of Transland Spatio-Temporal Data Model

Xiaohong Xin
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To the Graduate Council:

I am submitting herewith a dissertation written by Xiaohong Xin entitled "An Exploratory Data Analysis Approach for Land Use-Transportation Interaction: The Design and Implementation of Transland Spatio-Temporal Data Model." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Shih-Lung Shaw, Major Professor

We have read this dissertation and recommend its acceptance:

Bruce A. Ralston, Chanaka Edirisinghe, Cheng Liu

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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**AN EXPLORATORY DATA ANALYSIS APPROACH FOR
LAND USE-TRANSPORTATION INTERACTION: THE
DESIGN AND IMPLEMENTATION OF TRANSLAND
SPATIO-TEMPORAL DATA MODEL**

**A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville**

**Xiaohong Xin
May 2003**

DEDICATION

This dissertation is dedicated to my family.

ACKNOWLEDGEMENTS

Mentors make a difference! I was fortunate enough to collect several of the very best. They were all quite different, yet the qualities they shared had a lasting impact on my work in several fields. Their shared traits were high performance expectations, integrity and intellectual honesty, and a problem-solving attitude. These values left a lasting mark on me. The men are my Ph.D. dissertation committee members and friends.

I owe a special thank you to my dissertation committee chairman, Dr. Shih-Lung Shaw, for his help, guidance, and extraordinary hard work. A professional and friendship association with Dr. Shaw brought me to a research project awarded by Florida Department of Transportation (FDOT) in December 2000, which then directly led to my dissertation research. Much of the work we accomplished, I could not have done myself. More than anyone else, Dr. Shaw provided me with the continuous and extended academic education that geographers require. Further, he has graciously incorporated his entire family into my support network: his wife has aided me graciously and frequently; his two children have shared hospitality. Their sincere concern for my success on a day-by-day basis was of irreplaceable value. All dissertation writers suffer highs and lows. The Shaw's made my highs higher and my lows bearable.

Dr. Bruce A. Ralston provided my first strong impetus to associate with the University of Tennessee, Knoxville (UTK). We first met in 1993 in Lanzhou University, P.R. China. When I described my intentions to convert myself from an avid but amateur

reader in Geographical Information Systems (GIS) to an intellectually-informed and serious student of GIS, Dr. Ralston said, "visit UTK someday." That led, in two years, to my enrolling in UTK in the fall of 1995. Dr. Ralston, since 1995, served as my academic advisor, thesis committee chairman, and dissertation committee member. He has unselfishly given his time and counsel on all professional matters and guided my past seven years of work.

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UTK is truly filled with people of goodwill who have taken it on their shoulders in one way or another to help me succeed and whom I profusely thank here: the staff of Center of International Education (CIE) who helped me secure Elsie L. Crenshaw Student Aid Fund in the last semester when I could finish this dissertation writing.

This acknowledgement would not be complete without mention of the funding provided by the FDOT's University research program to support this dissertation research and the inputs from the our research collaborators in the Department of Civil and Environment Engineering at Florida International University.

Lastly among my friends, but perhaps most importantly for their distinct contribution, I want to thank Dr. Michael Chang, pastor of Knoxville Chinese Christian Church (KCCC), who encouraged my professional work and guided my spiritual growth, and the other members of the KCCC. They extended every personal courtesy to me for so many years. Their high standards for morality serve as an excellent example to me.

ABSTRACT

Land use and transportation interaction is a complex and dynamic process. Many models have been used to study this interaction during the last several decades. Empirical studies suggest that land use and transportation patterns can be highly variable between geographic areas and at different spatial and temporal scales. Identifying these changes presents a major challenge. When we recognize that long-term changes could be affected by other factors such as population growth, economic development, and policy decisions, the challenge becomes even more overwhelming. Most existing land use and transportation interaction models are based on some prior theories and use mathematical or simulation approaches to study the problem. However, the literature also suggests that little consensus regarding the conclusions can be drawn from empirical studies that apply these models. There is a clear research need to develop alternative methods that will allow us to examine the land use and transportation patterns in more flexible ways and to help us identify potential improvements to the existing models.

This dissertation presents a spatio-temporal data model that offers exploratory data analysis capabilities to interactively examine the land use and transportation interaction at use-specified spatial and temporal scales. The spatio-temporal patterns and the summary statistics derived from this interactive exploratory analysis process can be used to help us evaluate the hypotheses and modify the structures used in the existing models. The results also can suggest additional analyses for a better understanding of land use and transportation interaction. This dissertation first introduces a conceptual

framework for the spatio-temporal data model. Then, based on a systematic method for explorations of various data sets relevant to land use and transportation interaction, this dissertation details procedures of designing and implementing the spatio-temporal data model. Finally, the dissertation describes procedures of creating tools for generating the proposed spatio-temporal data model from existing snapshot GIS data sets and illustrate its use by means of exploratory data analysis.

Use of the spatio-temporal data model in this dissertation study makes it feasible to analyze spatio-temporal interaction patterns in a more effective and efficient way than the conventional snapshot GIS approach. Extending Sinton's measurement framework into a spatio-temporal conceptual interaction framework, on the other hand, provides a systematic means of exploring land use and transportation interaction. Preliminary experiments of data collected for Dade County (Miami), Florida suggest that the spatio-temporal exploratory data analysis implemented for this dissertation can help transportation planners identify and visualize interaction patterns of land use and transportation by controlling the spatial, attribute, and temporal components. Although the identified interaction patterns do not necessarily lead to rules that can be applied to different areas, they do provide useful information for transportation modelers to re-evaluate the current model structure to validate the existing model parameters.

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1 INTRODUCTION

Bringing time into geography is not a new topic. David Harvey speculated that the basic tenet of the geographic thought was to have “a general theory in geography that examined the interaction between temporal process and spatial form” (Harvey, 1969 p. 484). In fact, since it is detrimental to explore spatial problems by ignoring how they change over time, geographers have been studying geographic phenomena through putting an emphasis on processes and their dynamic characteristics. A land use-transportation system is one of many examples which geographers study. How interaction between land use development and transportation improvements affects spatial patterns over time is of great interest. The land use-transportation system includes several relationships between a transport system, activities, land use, and accessibility (Figure 1.1). Land uses, such as residential, industrial or commercial, determine the locations of human activities such as living, working, shopping, education or leisure. Human activities in space require spatial interaction or trips in the transport system to overcome the distance between the locations of activities. Infrastructure in the transport system creates opportunities for spatial interaction and can be measured as accessibility. Accessibility in space co-determines location decisions and so results in changes of the land use system.

Effects of transportation system changes on land use, and vice versa, occur at varying spatial and temporal scales. For example, the construction of a new rail transit line tends to have large effects on land use changes along the transit line corridor and

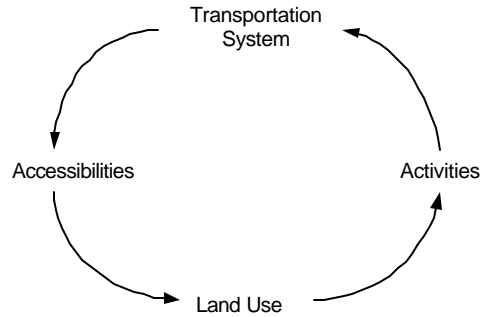


Figure 1.1: Basic Interactions in a Land Use-Transportation System

around the rail stations than on the urban area as a whole. A highway construction project may introduce a traffic increase shortly after its completion and lead to some land use changes in its immediate vicinity. However, its impacts on land use patterns at the regional scale may be insignificant in both short and long terms due to the relatively small changes to the accessibility levels on other parts of the metropolitan area. Wegner and Fürst (1999) classify eight types of major urban subsystems into those that experience very low changes, slow changes, fast changes, and immediate changes (Table 1.1). Physical infrastructure such as transportation networks and land use patterns based on existing buildings take longer time to exhibit significant changes. People and firms, on the other hand, show faster adjustments to changes in traffic conditions and fluctuations in demand with respect to their location choices and travel choices. Identifying these complex changes at varying spatial and temporal scales presents a major challenge. When we recognize that long-term changes could be affected by other factors such as population growth, economic development, and policy decisions, the challenges becomes even more overwhelming.

Table 1.1: Urban Change Processes (Source: Wegner and Fürst, 1999, p. 43)

| Urban Change Processes | Examples |
|------------------------|--|
| Very slow change | <i>Networks</i> (e.g., transport networks, communications networks): are the most permanent elements of cities. <i>Land use</i> : distribution is often stable; changes are incremental. |
| Slow change | <i>Workspaces</i> (e.g., warehouses, office buildings, shopping centers): exist much longer than the firms or institutes that occupy them. <i>Housing</i> : exist longer than households that live in it. |
| Fast change | <i>Employment</i> : refers to firms that open, close, expand, or relocate. <i>Population</i> : refers to households that form, grow, decline, dissolve, or relocate. |
| Immediate change | <i>Goods transport</i> : adjusts quickly to changes in demand. <i>Travel</i> : adjusts quickly to changes in traffic conditions. |

Use of exploratory data analysis (EDA) for spatio-temporal data is a promising method to empirically reveal spatial and temporal interaction by means of case studies. GIS have been used for exploratory analysis of spatial patterns, and time series analysis has been used to study temporal changes. However, there are few tools available for the exploratory analysis of spatio-temporal data. The state of the art in GIS has evolved to where the need for exploratory spatio-temporal analysis tools can be addressed. Existing GIS software contains spatial analysis tools, such as buffering, overlay, and spatial selection. Further, the past two decades have marked by massive data collection so that the availability of time-stamped land use and transportation databases is no longer a constraint. Recently, GIS software has evolved from geometrically based hybrid relational database management systems to behaviorally based object-oriented database management systems.

However, much work remains to be done. Currently, there are only a few proposed approaches to modeling spatio-temporal processes in GIS. There is a need for data models that will support spatio-temporal EDA. Once such data models are articulated, tools for converting existing snapshot spatial data model to that data model need to be developed. Finally, EDA tools for exploring the resulting database remain to be built. It is these tasks that this dissertation will address within the specific problem domain of land use-transportation interaction. This is accomplished by building upon the recently developed geodatabase model and COM technology used in ArcGIS 8 (Environmental Systems Research Institute, Redland, CA). The approach taken here is designed to preserve the query, analysis, and spatial indexing tools already in ArcGIS, while facilitating exploratory spatio-temporal analysis.

This dissertation explores land use-transportation interaction using historic data sets. It centers on how to design and implement the Transland spatio-temporal data model to store, manage, and retrieve the data. The purposes of this dissertation are:

- To review existing spatial data models and spatio-temporal data models and introduce a conceptual framework for the Transland spatio-temporal data model.
- To develop a systematic method for explorations of various data sets relevant to land use and transportation interaction
- To design and implement the Transland spatio-temporal data model, which will incorporate and extend approaches suggested in the literature.

- To create tools for the proposed spatio-temporal data model from existing snapshot GIS data sets and illustrate its use by means of exploratory spatio-temporal data analysis

Chapter 2 discusses the concepts and theories relevant to the Transland spatio-temporal data model. This chapter consists of three parts. The first part reviews spatial data models and discusses their implications for spatio-temporal data models. The second part reviews existing attempts at developing spatio-temporal data models. Based on these approaches, the final section of the chapter proposes the Transland spatio-temporal data types and addresses both theoretical and practical issues about the representation of space and time within spatial data models.

Chapter 3 lists six scenarios relevant to land use-transportation interaction over space and time. This chapter applies a conceptual framework (including three components – land use, transportation, and time) to identify two scenarios that are relevant to spatial patterns and four others about temporal patterns. The chapter also presents the kinds of functions to be included in Transland for every scenario. The description of the steps lays a conceptual foundation for the design and implementation of Transland spatio-temporal data models, which is to be presented in the following two chapters.

Chapter 4 contains detailed procedures for the design of the Transland spatio-temporal data model. UML class diagrams with spatial classes, provided by the ArcGIS

data model, act as templates for the Transland class packages. These class packages are needed to address the scenarios presented in Chapter 3.

Chapter 5 demonstrates the methods of implementing the Transland classes from the Transland packages. The chapter then describes procedures for creating the Transland classes from existing landuse and transportation snapshot databases. Once the temporal GIS databases are developed, the chapter presents tools for exploratory spatio-temporal data analysis of land use-transportation interaction.

Chapter 6 finally evaluates the Transland spatio-temporal data model and points out future research directions. Suggestions for enhancing the performance of the system developed in the dissertation are presented. The chapter ends with a discussion of the strengths and weakness inherent in exploratory data analysis.

2 KEY CONCEPTS

Research on spatio-temporal data models over the last two decades has not developed to the extent that a framework with theories, concepts, and principles exists to lay a solid foundation for the Transland spatio-temporal data model. Prior to a discussion of the issues of the design and implementation of Transland, this chapter will present several relevant concepts that are crucial to an understanding of its spatio-temporal data model. The chapter first reviews spatial data models and explores their implications for developing spatio-temporal data models. It then reviews existing attempts at developing spatio-temporal data models. Finally, the chapter introduces the Transland spatio-temporal data types, which act as major components for the Transland spatio-temporal data model.

2.1 Spatial Data Models

One popular spatial data model, widely adopted by conventional GIS software, is snapshot spatial data model that represents the locations and attributes of a particular phenomenon (e.g., land use) at a fixed time instant (e.g., March 22, 2000) (Figure 2.1). The spatial data model cannot handle spatial changes over time, which is critical for exploring temporal patterns for the land use-transportation interaction.

Database management systems (DBMS) are general-purpose software systems for the implementation of data models. From the 1970s onwards, DBMSs have been and

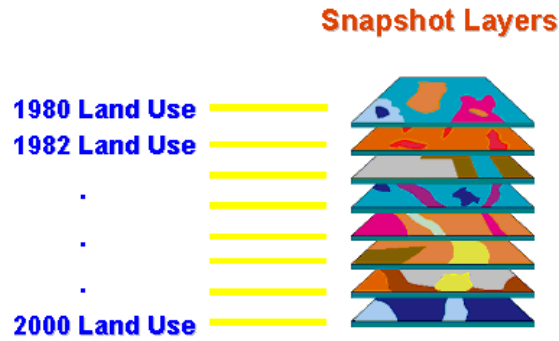


Figure 2.1: Snapshot Spatial Data Model

remain an intensely fought-over battlefield. The original protagonists were, in one corner, hierarchical and network DBMSs, and in the other corner, relational DBMS following (more or less) the principles first developed by E. F. Codd in 1970 (Codd, 1970). During the 1980s the relational systems came to dominate the marketplace. In the late 1980s and the 1990s, new DBMSs arose, as so-called object-oriented system, and the hybrid of it with the relational DBMSs, as object-relational DBMSs. By providing users with interfaces to store, access, and maintain data defined in data models, DBMSs play a central role for developing spatial data models (represented by the snapshot spatial data model) whose progress witnessed the evolution of DBMSs for the last three decades.

2.1.1 Relational DBMS for Spatial Data Models

A relational DBMS contains a set of *relations*. Each relation is also called a *table*. A well-defined structure for the table is a *relational schema*. A set of relational schema is named a *database schema*. A relational schema consists of a set of attributes that represents the properties of real world entities. Each attribute has a name that is

unique within the relational schema and has a scalar domain such as integer, double, string, or date. A single element of a relation is called a *tuple*.

Figure 2.2 presents a table whose tuples represent attributes for parcels in a snapshot GIS layer in 1994. The tuples in the table describe the properties of parcels. For example, the tuple (2074, Vacant) contains a land use type for parcel 2074. The table corresponds to a relational schema:

```
R = (ParcelID : INTEGER PRIMARY KEY,
     Landuse  : CHAR(50)
    )
```

A relational DBMS supports Structured Query Language (SQL) (Date and Darwen, 1993; Melton and Simon, 1993). It also supports several integrity constraints, for instance, *primary keys*, *foreign keys*, and *referential integrity*. A primary key is an attribute (or a set of attributes) of a relation whose value uniquely identifies a tuple in a relation. In the relational schema **R** in Figure 2.2, attribute ParcelID is denoted as the primary key. A foreign key is an attribute (or a set of attributes) of one table that contains only the values of the primary key of another table. A foreign key is used when

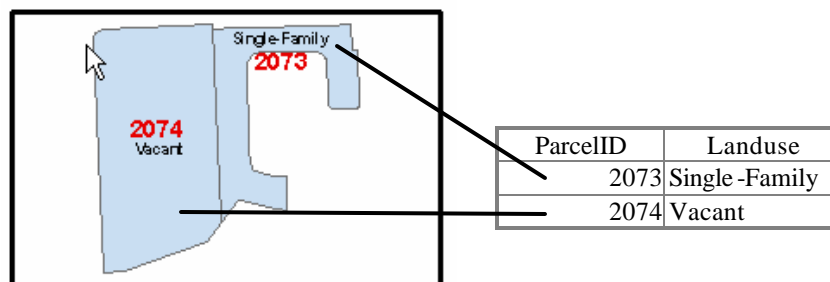


Figure 2.2: A Snapshot GIS Layer with its Tuples

there is more than one table and associations exist between the tables, which is not the case in Figure 2.2. Referential integrity constraints for a relation demand that each of its foreign key values must also exist as a primary key in the other table.

A major drawback of the relational data model is its inability to handle user-defined data types. This restricts the expressive power of the data structures, especially for spatial data. To overcome this drawback, relational data models are extended to support complex spatial data. Divided and integrative architectures are two methods that relational spatial data models use to combine the spatial data and built-in aspatial data.

Layered and dual architectures are two methods that the divided architecture uses to combine the spatial data with aspatial data. GEOVIEW (Waugh and Healey, 1987) and SIRO-DBMS (Abel, 1989) are two examples of the layered architecture. They represent spatial data types (i.e., geometries) with non-interpreted byte strings. These spatial data types are stored in a separate spatial layer that is above the relational DBMS (Figure 2.3(a)). Georelational spatial data models used by ARC/INFO (Morehouse, 1989) and GRDM (Hadzilacos and Tryfona, 1996; Gadia and Chopra, 1993) use the dual architecture. They develop proprietary file formats to store the spatial data and use a relational data model to store the attributes. Another software layer is built above them to handle communication between the spatial data in the proprietary file system and the attribute data in the relational DBMS (Figure 2.3(b)).

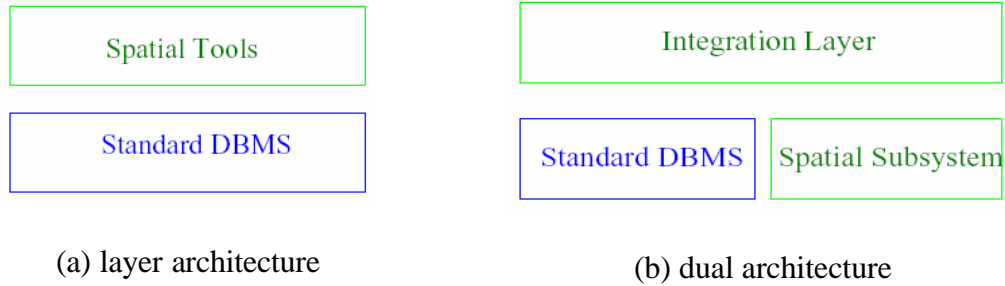


Figure 2.3: Two Types of Divided Architectures

Unlike the divided architecture that holds a disparity between spatial and attribute data, the integrative architecture does not differentiate between standard data types (e.g., integer) and spatial data types (e.g., polygon), between spatial and attribute query mechanisms, and between the methods of indexing spatial and attribute data. Oracle Spatial ("Oracle Spatial Data Sheet," 2002) uses integrated architecture with functions and procedures to enable spatial data to be stored, accessed, and analyzed quickly and efficiently in an Oracle9i database. Oracle spatial supports a relational data model (besides an object-relational data model) for representing geometries in spatial data. The relational DBMS uses a table with a predefined set of columns of type NUMBER and one or more rows for each geometry instance. Basic components of the integrative architecture consist of a complex data type system and a storage/buffer manager along with a high-level user interface. The user interface with its user-defined application program creates integrative links between the other components. The integrated architecture handles spatial data types and queries more efficiently than the divided architecture.

2.1.2 Object-oriented DBMS for Spatial Data Models

Relational DBMSs have inherent restrictions. They only support single relational data structures and enforce the restrictions on relations. Object-oriented DBMSs overcome these deficiencies by providing functions to store complex abstract data types (ADT) with fewer relational restrictions. In comparison to relational data models that are key-based, object-oriented data models are identify-based (Steiner, 1998). In other words, an object can be referenced via a unique system-generated number that is independent of the value of its primary key. This number is called the object identifier (OID). It differs from a key in a relational DBMS by the fact that a key value may change, but the OID still represents the same real-world object. The same OID may have different keys in different relations.

In a relational DBMS, information about a complex object is often scattered over many relations, which leads to a loss of direct correspondence between a real world object and its database representation. Object-oriented DBMSs allow the storage of all information concerning an OID as one single database object. Each object consists of an OID, its state and behavior. The state of an object is specified from a combination of simple attributes, reference attributes, or complex references. The behavior of an object is specified by operations.

Figure 2.4 shows two snapshot GIS layers in 1994 and 1998. This example is used to explain the concepts of objects and objects components – OID, state, and behavior.

The following notation defines a class `ParcelChange` to represent parcel OID changes during 1994 and 1998 in Figure 2.4.

```

Class ParcelChange {
  State ParcelID1994:GEOMETRY;
  State ParcelID1998:GEOMETRY;
  behavior TraceID(StartYear:INTEGER, EndYear:INTEGER,
                  ParcelID1994:GEOMETRY);
}

```

where *state* `ParcelID1994` denotes geometry entities in 1994 with parcel OIDs as 2073 and 2074. Similarly, *state* `ParcelID1998` denotes geometry entities in 1998 with parcel OIDs as 2721, 2719, 2812, and 2825. *Behavior* `TraceID` keeps track of the changes of parcel OID between these two years. For example, when `startYear` is 1994, `EndYear` is 1998, and `ParcelID1994` is 2073, `TraceID` (1994, 1998, 2073) is a function for detecting

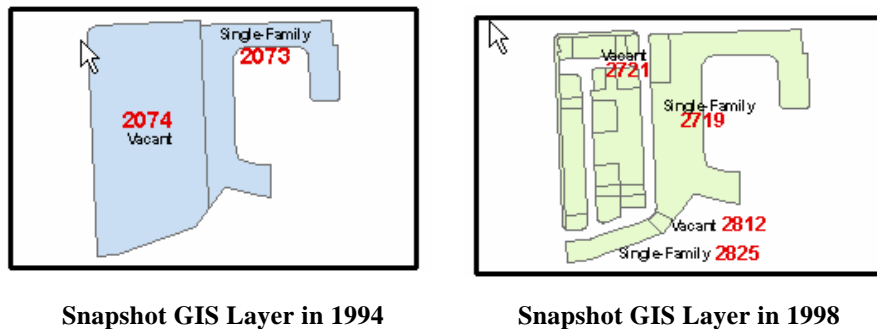


Figure 2.4: Snapshot GIS Layers

how the OIDs for the 1994 parcel 2073 change from 1994 to 1998. A result from `TraceID` returns an array (2071, 2719, 2812, 2825) indicating that 1994 Parcel 2073 changed its OID as a set of parcels with OIDs as 2071, 2719, 2812, and 2825 in 1998.

As a class constructed for the object-oriented DBMS, the class `ParcelChange` can also have its class dependencies that reflect encapsulation, inheritance, and polymorphism, characterizing three object-oriented features.

Encapsulation, also called information hiding, means each class manages its own states and behaviors. Therefore, states and behaviors constructed with encapsulation may manipulate states and behaviors in other classes using a set of predefined behaviors, thus ensuring data independence. The states and behaviors in `ParcelChange` associated with Figure 2.4 are examples of encapsulation. Accessing *state* `ParcelID1994` and *state* `ParcelID1998` requires a class `GetID` with such behaviors as `GetParcelID1994` and `GetParcelID1998`.

```
Class GetID {  
    Behavior GetParcelID1994();  
    Behavior GetParcelID1998();  
}
```

Inheritance refers to an associative relationship between classes. Classes can be arranged in hierarchies so that subclasses inherit states and behaviors from a parent class. In fact, when subclasses inherit all states and behaviors from a parent class, they can also define their own states and behaviors that are different from those of the parent class.

Example 1 shows subclasses `ParcelLUChange` and `ParcelCodeChange` with an

inheritance from `ParcelChange`, which acts as a parent class in this example to keep track of changes of land use types and land use codes, respectively.

Example 1:

```
Class ParcelChange {  
  
    State ParcelID1994:GEOMETRY;  
    State ParcelID1998:GEOMETRY;  
    behavior TraceID(StartYear:INTEGER, EndYear:INTEGER,  
                    ParcelID1994:GEOMETRY);  
}  
SubClass ParcelLUChange {  
    State ParcelID1994:GEOMETRY;  
    State ParcelID1998:GEOMETRY;  
    behavior TraceID(StartYear:INTEGER, EndYear:INTEGER,  
                    ParcelID1994:GEOMETRY);  
    behavior TraceLU(StartYear:INTEGER, EndYear:INTEGER,  
                    ParcelID1994:GEOMETRY);  
}  
SubClass ParcelCodeChange {  
    State ParcelID1994:GEOMETRY;  
    State ParcelID1998:GEOMETRY;  
    behavior TraceID(StartYear:INTEGER, EndYear:INTEGER,  
                    ParcelID1994:GEOMETRY);  
    behavior TraceCode(StartYear:INTEGER, EndYear:INTEGER,  
                      ParcelID1994:GEOMETRY);  
}
```

Polymorphism reflects the flexibility of classes. It means that the same behavior performs differently when it is applied to different classes. It also means that different behaviors from different classes can interpret the same message in different ways. In Example 2, `TraceID(StartYear:INTEGER, EndYear:INTEGER, ParcelID1994:GEOMETRY)` from class `ParcelChange` is a polymorphism counterpart for `TraceID(EndYear:INTEGER, ParcelID1994:GEOMETRY)` in class `ParcelByEndYear`. They hold the same behavior name `TraceID` in different classes, but with different input parameters. `TraceID` in the class `ParcelByEndYear` does not have a `StartYear`.

Example 2:

```
Class ParcelChange {
    State ParcelID1994:GEOMETRY;
    State ParcelID1998:GEOMETRY;
    behavior TraceID(StartYear:INTEGER, EndYear:INTEGER,
                    ParcelID1994:GEOMETRY);
}
Class ParcelByEndYear {
    State ParcelID1994:GEOMETRY;
    State ParcelID1998:GEOMETRY;
    behavior TraceID(EndYear:INTEGER, ParcelID1994:GEOMETRY);
}
```

The illustration of the class construction provides an understanding of methods that spatial data models use for identifying spatial data types with object-oriented DBMSs. The literature indicates that there are no spatial data models that actually implement object-oriented DBMSs although there exist many spatial data models proposed with object-oriented spatial data types. For example, Choi and Luk (1992) propose a bi-level (i.e., geographic and geometric) object-oriented spatial data model. Each level applies three main constructs: objects, classes, and functions. Objects are divided into primitive and non-primitive objects. Primitive objects are the built-in data types. Non-primitive objects are those derived data types such as paths, physical regions, or themes at the geographical level, and points, lines, and polygons at the geometric level.

2.1.3 Object-relational DBMS for Spatial Data Models

Object-relational DBMSs are not only able to represent object-oriented features like encapsulation, inheritance, and polymorphism, but have access to relational integrity rules as well. Object-relational DBMSs are becoming popular for developing spatial data

models due to their advantage for managing complex user-defined spatial data types (vs. the relational data models) and supporting a spatial SQL (vs. the object-oriented data model). Moreover, object-relational DBMSs are superior to object-oriental DBMSs because of their ability to support the transition from legacy spatial data that were previously kept within relational DBMSs.

Table 2.1 is a relational table representing parcel polygons from a snapshot GIS layer with object-relational DBMSs. The table supports object-oriented concepts with a field “Shape”, which belongs to a data type called BLOB (binary large objects).

There are several major relational DBMS vendors developing products (e.g., Oracle Spatial, Informix Spatial Data Blade, IBM DB2 Spatial Extender) with object-relational data models to manage spatial data. Commercial GIS software vendors have also started to adopt object-relational DBMSs. ESRI’s ArcGIS data model is a spatial data model using object-relational DBMSs (Zeiler, 1999). With improvements over its predecessor – Georelational data model, ESRI’s ArcGIS data model supports a rich collection of objects and features that are adaptations of concepts from object-oriented

Table 2.1: A Table for a Snapshot GIS Layer

| Shape | OID | Parcel1998 | LU1998 |
|---------|-----|------------|----------------|
| Polygon | 21 | 2721 | Vacant |
| Polygon | 12 | 2719 | Single -Family |
| Polygon | 3 | 2812 | Vacant |
| Polygon | 1 | 2825 | Single -Family |
| Polygon | 15 | 2719 | Single -Family |

DBMSs. Figure 2.5 presents a polygon class extracted from one of ArcObjects object model diagrams. The polygon class has prototypes for states (e.g., ExteriorRingCount and InteriorRingCount) and behaviors (e.g., Close and FindExteriorRing) as depicted in Figure 2.5. The polygon class also maintains object-oriented characteristics in association with other classes. A simplified class hierarchy (Figure 2.6) shows the polygon class is inherited from Geometry class through Curve class and PolyCurve class (indicated with arrows in Figure 2.6). In another words, the Polygon class inherits class characteristics from all of its parent object classes. At a fundamental level, the ArcGIS data model organizes the objects and features in relational tabular structures. In fact, their implementation subsumes the relational DBMSs. The ArcGIS data model includes a specification for a number of feature classes, raster data sets, and other tables plus a series of relationships among the tables. The information types in the ArcGIS data model include object data types (e.g., tables, relationships) plus GIS-specific content (e.g., geometry, polygon). There will be a detailed description about the ArcGIS data model in Chapter 4.

2.2 Existing Spatio-temporal Data Models

Figure 2.7 depicts a data model and its components. This figure indicates that the data model captures essential information from the real world based on functional and database requirements (Elmasri and Navathe, 1994). The functional requirements (indicated as hatched arrows) refer to the user-defined data types, operations, and

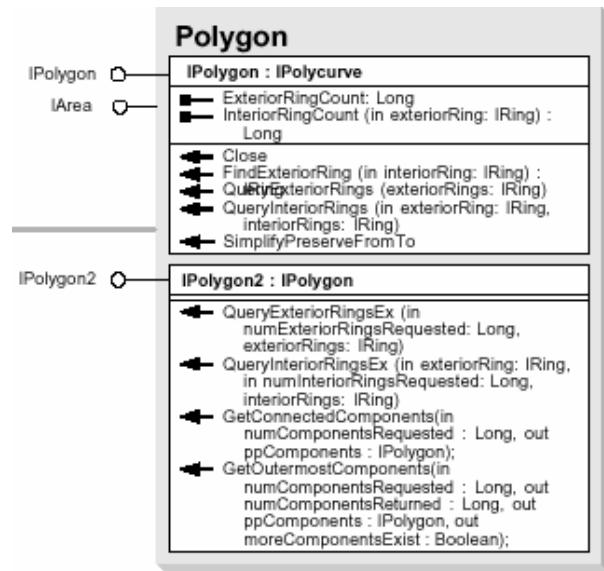


Figure 2.5: A Polygon Class (Zeiler, 2001)

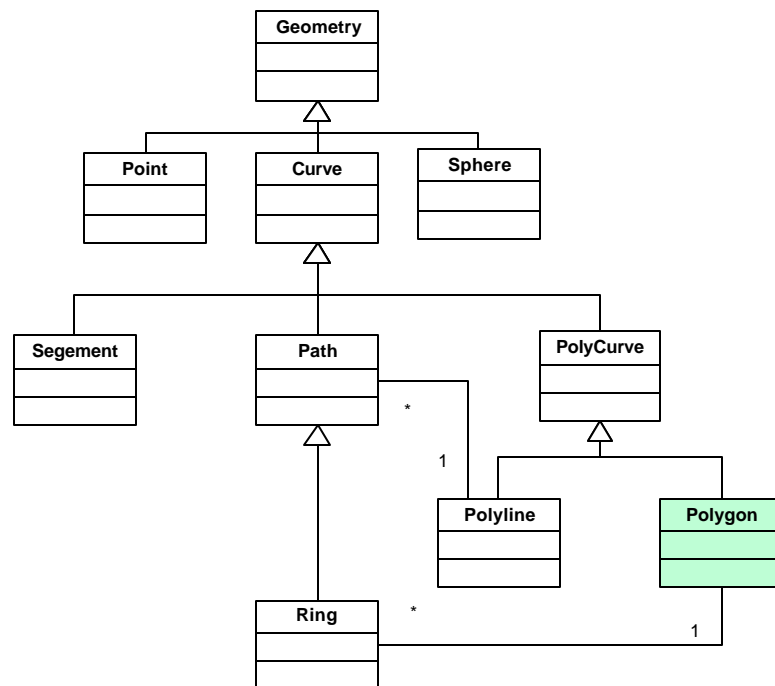


Figure 2.6: A Polygon Class and its Predecessors (Zeiler, 2001)

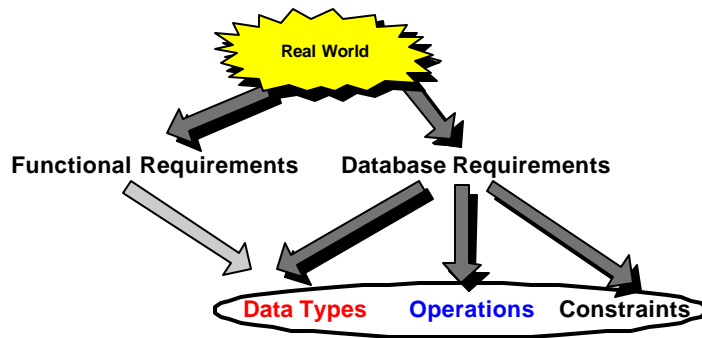


Figure 2.7: Data Model Components (Source: Steiner, 1998)

integrity constraints that will be customized and applied to the data model. The database requirements (indicated as gray arrows) directly lead to the specification of data types, operations, and integrity constraints for real world objects. Let us use ESRI Georelational data model to further explain the above concepts. As an example of a spatial data model, the Georelational data model is implemented within a relational DBMS, which raises database requirements for the data model to consist of three data model components -- spatial data types (e.g., points, lines, polygons), spatial operations (e.g., buffering, overlaying), and relational integrity constraints (including accessing methods). Specific user needs as functional requirement are proposed for different applications. For example, land use and transportation data such as roads and parcels are specified as spatial data types (i.e., lines and polygons) according to the needs from exploring spatial and temporal data relevant to land use-transportation interaction. Operations and constraints corresponding to the interaction can also be developed for handling and facilitating land use and transportation data queries.

Spatio-temporal data models, in the same manner as the Georelational data model, employ the functional and database requirements. However, means and ways are different when researchers specifically define spatio-temporal data types, spatio-temporal operations, and spatio-temporal constraints to meet the requirements. In general, they apply two approaches to altering the data model components. One approach not only alters data types, but also the other two components so that spatial data models may be extended or integrated to become spatio-temporal data models. By extension it is meant that the approach involves the development of either spatio-temporal operations or integrity constraints. By integration it is meant that every component of a data model is “tuned” for a spatio-temporal use. Modeling of Application Data with Spatio-temporal features (MADS) is an example extending spatial schemas for a spatio-temporal use (Parent et al., 1999). As an object-relational conceptual data model designed in cooperation with applications related to land management or utility networks, MADS allows the specification of integrity rules for data models as well as relationships that define space and/or time-related semantics. There exists no comprehensive research for the integration of spatial data models into spatio-temporal data models. Nevertheless, there are several ongoing projects – CHOROCHRONOS by the European Union, TimeCenter by cooperative research groups of scientists from European Countries and the United States, and Spatial and Temporal Object Databases (2002) at Keele University, United Kingdom. Their research efforts cover many theoretical and practical issues. Since the extension and integration of the spatio-temporal data models involve many unsolved research topics, this dissertation is not going to further review that approach, but shift to the second approach, which tackles only the data types and

represents spatio-temporal data types through available data type “date” from spatial data models and abstract data types. This approach forms the conceptual foundation on which this dissertation bases its proposed spatio-temporal data model.

2.2.1 Data Type “Date”

One easy way of developing spatio-temporal data types within spatial data models is to use data type “date.” Applications adopting the data type “date” are mostly built on relational or object-relational DBMSs. The data type “date” specifies user-defined time attributes and timestamp attributes in spatial data model schemas, which means that timestamps are defined either as attributes of a relational table or time instants assigned as a timestamp of a relational table (Clifford, 1983; Lum, et al., 1984; Snodgrass and Ahn, 1985; Armstrong, 1988; Hunter and Williamson, 1990; Stickler, et al., 1992). This method is simple, but it has problems in terms of its data maintenance and efficiency. The lack of direct query support for spatio-temporal data leads to complex query operations, which in turn results in the difficulty of maintaining the data model. It is also unable to solve data redundancy from the snapshot spatial data model, which manages time-varying spatial data with separate GIS layers.

2.2.2 Spatio-temporal Abstract Data Types (ADT)

One of the basic ideas behind spatio-temporal data models is that, in addition to the normal built-in data type defined as “date”, user-defined types may also be employed.

These types may be used in the same way as built-in types. For example, columns in relational tables may be defined as taking values of user-defined types, as well as built-in types. A user-defined Abstract Data Type (ADT) definition encapsulates attributes and operations in a single entity. An abstract data type (ADT) is defined by specifying a set of declarations of the stored attributes that represent the value of the ADT, the operations that define the equality and ordering relationships of the ADT, and the operations that define the behavior (and any virtual attributes) of the ADT. ADTs can also be defined as subtypes of other ADTs. A subtype inherits the structure and behavior of its supertypes (multiple inheritance is supported). Instances of ADTs can be persistently stored in the database by storing them in columns of tables. Points, line, and polygons in the Georelational data model are examples of spatial ADT stored in table columns. Spatio-temporal ADT is a research topic that attracts many researchers, and is represented by the Event-based Spatio-temporal Data Model, the STComposite data model, and the Worboys data model.

The Event-based Spatio-Temporal Data Model (ESTDM) (Peuquet and Duan, 1995) represents dynamic geographic objects (Figure 2.8) through organizing changes under an event list that is composed of individual event entries. Each event entry has a time stamp and consists of a set of components. A component stores the new value of all grid cells that experienced changes of a specific attribute from t_{i-1} to t_i and the locations of grid cells that changed to the new value. Run-length encoding is employed to store the locations of grid cells with changing values as token arrays in order to reduce the storage space requirement. Each grid cell is equivalent to the smallest spatial feature stored in

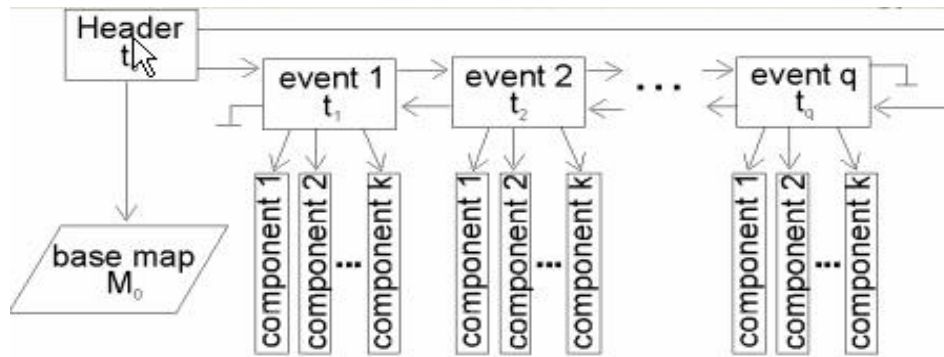


Figure 2.8: Event-based Spatio-Temporal Data Model (ESTDM) (Source: Peuquet and Duan, 1995)

the space-time composite model that permits the storage of its change history. The ESTDM also includes a header with a time stamp of t_0 pointing to the base raster layer of the initial state of the entire study area. This design allows the ESTDM to record only amendments with respect to the initial and previous states. ESTDM has several shortcomings. ESTDM is developed only for raster-based GIS. It might be insufficient to meet needs from applications requiring vector topology. Moreover, ESTDM relies on ADT programming for building the event lists. The integration of the event list with DBMSs needs sophisticated programming skills.

The Space-Time Composite (STComposite) data model (Langran and Chrisman 1988, Langran 1992) improves the snapshot spatial data model by combining separate GIS layers representing different time points into a single STComposite GIS layer of all changes that have occurred over all time periods. Each record of the STComposite GIS layer represents the smallest geographic unit that experienced changes in history and is

assigned with time stamps to keep track of its changes over time. For example, Figure 2.9 shows an STComposite GIS layer that combines the land-use parcels of T1, T2, T3, and T4. The time stamps indicate that the land parcel with a solid color existed as a rural land-use type all the time and the one with a crossed hatch changed to urban land-use from rural land use starting at T2. Implementing STComposite GIS layers does not need extra procedures on ADT programming. The smallest geographic units, in comparison with the event list unit, gain spatial intactness over a span of time, but lose an ESTDM feature with the event lists carrying spatial information across areas of interest.

Worboy (1992, 1994) proposes an object-oriented spatio-temporal data model that represents objects as two-dimensional spatial objects along with a third dimension for the event time associated with each object (Figure 2.10). Conceptually, Worboys data model combines the characteristics of ESTDM and STComposite data model in such a way that the data are organized along a temporal dimension (e.g. event lists) and a spatial dimension (e.g., smallest geographic units). The temporal dimension of Worboys data model, according to its definition, is orthogonal to the spatial dimension. The basic

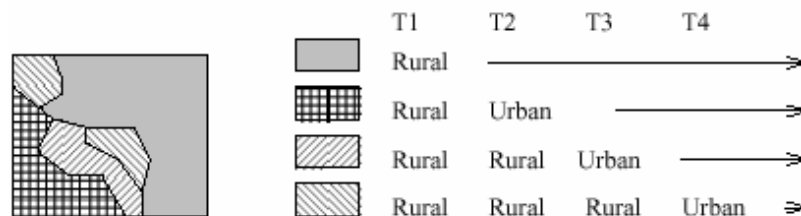


Figure 2.9: Spatio-Temporal Composite (STComposite) Data Model (Source: Langran, 1989)

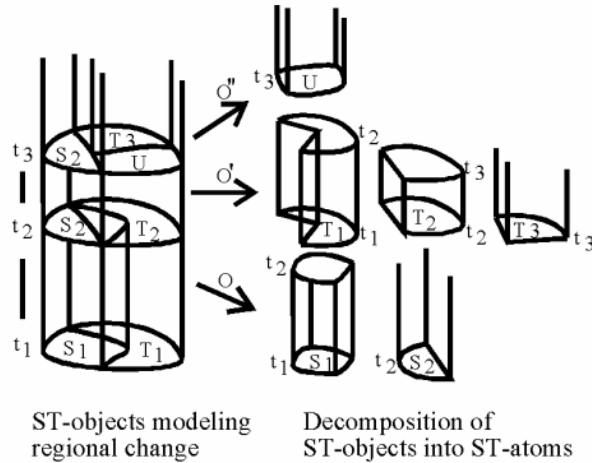


Figure 2.10: ST-objects and ST-atoms in Worboys Data Model (Source: Worboys, 1992)

elements in the data model are spatio-temporal atoms that have homogeneous properties in both space and time. The spatio-temporal atoms (ST-atoms) form spatio-temporal objects (ST-objects) that represent changes of real world entities. The data model maintains persistent object identifiers for both ST-atoms and ST-objects in order to uniquely keep track of their associations and the changing history. Worboys (1998) later extended this approach to a spatio-bitemporal model that includes both event time and database time as two orthogonal axes to record the existence of an object in the real world and in a database system, respectively.

Worboys data model implies that the ST-objects and ST-atoms may reflect user perspectives. Accordingly, for example, arrows with O , O' , and O'' in Figure 2.10 could be an extension of the temporal dimension or other non-temporal user criteria useful to decompose ST-atoms from ST-objects. If O is for land use types (i.e., O for urban land, O' for rural land, and O'' for vacant land), ST-atoms in the figure are grouped as urban

land, rural land, and vacant land with each ST-atom delineated with a spatial (e.g., S1) and a temporal extent (e.g., t1 and t2). O could conform to temporal units for ESTDM and spatial units for the STComposite data model so that the new ST-atoms are grouped by a temporal order (O is an event list, t1, t2, t3) and by a spatial order (O is the smallest spatial unit).

Worboys data model with the implication of the criteria O is a conceptual data model. Its implementation requires object-oriented DBMSs. The literature does not present research on its implementation with object-oriented DBMSs. On the other hand, Raza and Kainz (1998) attempt to implement Worboys data model based on the concepts of STComposite data model with a relational DBMS (Georelational spatial data model). Their implementation does not possess the ability of extending the criteria O to other formats of ADT.

2.3 Proposed Transland Spatio-Temporal Data Model

Transland spatio-temporal data types form a major component for proposing the Transland spatio-temporal data model. A data model M can be described, modified, and accessed in a uniform way, is expressed as $M = (DT, OP, C)$. The data model M includes three components, data types DT , query operations OP , and integrity constraints C (Steiner, 1998). A corresponding spatial data model enhancing the three components of the data model can be expressed as $M^S = (DT^S, OP^S, C^S)$. The temporal extension as discussed above, when applied for M^S , results into a spatio-temporal data model reflected

as $\mathbf{M}^{\text{ST}} = (\mathbf{DT}^{\text{ST}}, \mathbf{OP}^{\text{ST}}, \mathbf{C}^{\text{ST}})$, where time is stamped on every component of the spatial data model. Its data types accommodate time-varying spatial data. Its query operations are redefined with spatial, temporal, and spatio-temporal functions (Faria, et al., 1998). Additionally, each integrity constraint in the spatial data model \mathbf{C}^{S} has a temporal version \mathbf{C}^{ST} .

The data types \mathbf{DT} are the first, compared with the operations \mathbf{OP} and the constraints \mathbf{C} , to reflect changes enforced for applications. The literature reveals that spatio-temporal data models developed from spatial data models usually start with the design and implementation of new data types and data structures (refer to section 2.2). Query languages and access methods, although they are components equally important to the data types in data models, are the next for modification. The dissertation mainly tackles the construction of spatio-temporal data types \mathbf{DT}^{ST} . There are also some efforts engaged to facilitate queries for the spatio-temporal data types. Indexing methods in association with the access methods is not included in the dissertation.

This section serves as a conceptual foundation for the design and implementation of the Transland spatio-temporal data model. The following section discusses two concepts needed to conceptually propose the Transland spatio-temporal data model. One is about whether the data model is built upon a spatial data model or a temporal model. The other is how to use time-stamping methods to integrate time with spatial data types to form spatio-temporal data types.

2.3.1 The Temporal Extension of Spatial Data Models

Spatio-temporal data models may be developed through a spatial extension (i.e., adding the space component on top of a temporal data model) or a temporal extension (i.e., adding the time component on top of a spatial data model). Paton, et al. (2000) favor the spatial extension because the provision of a collection of spatial types within a temporal database yields a spatio-temporal data model that only requires extending the set of supported types (to include, say, points, lines, and polygon). By contrast, the temporal extension requires not only extending the set of supported types (instants and intervals), but also making provisions for all (or at least many) spatial data types to be associated with a history. Erwig (1999) also supports the spatial extension and mathematically proves that spatio-temporal objects are special cases of temporal objects. Meanwhile, temporal database research has contributed many proposals that facilitate the spatial extension (Navathe and Ahmed, 1989; Sarda, 1990 and 1993; Dey, et al., 1996; Bertino, et al., 1996).

While there are several groups (e.g., TimeCenter, National Technical University of Athens) conducting research on the spatial extension of temporal data models, an integrated support for spatial data in a temporal data model is still largely absent. In fact, the spatial extension has fewer implementations than the temporal extension according to the literature. Additionally, the temporal database technology that the spatial extension relies on is still under research and is not as well developed as the spatial database technology. The temporal extension of spatial models, therefore, is the research focus of

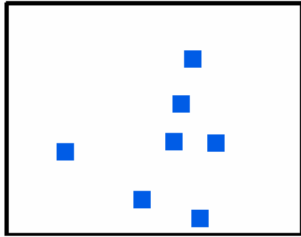
this dissertation so that the exploration of adding the time component to a spatial data model may lead to an operational spatio-temporal data model.

However, spatial data models only cope with snapshot GIS layers. Procedures are needed to add time-stamps into the snapshot GIS layers, then use the time-stamps to generate STComposite GIS layers, which is a focus of the data model proposed for the dissertation. Examples used in the next section illustrate how to time-stamp spatial data types in spatial data models and consequently construct spatio-temporal data types from a STComposite GIS layer.

2.3.2 Spatial Data Time-stamping in Snapshot GIS Layers

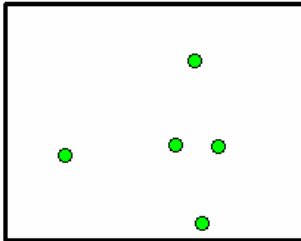
The following section recognizes two methods commonly used for snapshot spatial data models to time-stamp spatial data types. With relational integrity constraints applied, they are called tuple time-stamping and object time-stamping (Steiner, 1998).

A tuple represents a single element of a relation. Tuple time-stamping means each row carries a valid or database time denoting when the tuple exists or is valid in a database. While it is the easiest way of directly handling time, tuple time-stamping does not overcome the disadvantage of data redundancy in the snapshot spatial data models. Figure 2.11 presents snapshot spatial GIS layers in 1994, 1996, and 1999 with their individual attribute table carrying time-stamps as fields, such as “T_1994”, “T_1996”,



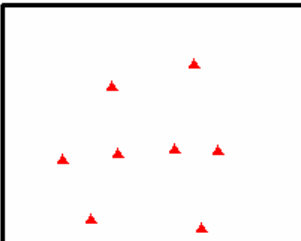
Snapshot GIS Layer 1994

| OBJECTID | TYPE | ID | T_1994 |
|----------|----------|-----|--------|
| 1 | Portable | 14 | 1 |
| 2 | Portable | 94 | 1 |
| 3 | Portable | 289 | 1 |
| 4 | Portable | 311 | 1 |
| 5 | Portable | 346 | 1 |
| 6 | Portable | 313 | 1 |
| 7 | Portable | 374 | 1 |



Snapshot GIS Layer 1996

| OBJECTID | TYPE | ID | T_1996 |
|----------|----------|-----|--------|
| 1 | Portable | 14 | 1 |
| 2 | Portable | 94 | 1 |
| 3 | Portable | 289 | 1 |
| 4 | Portable | 311 | 1 |
| 5 | Portable | 346 | 1 |



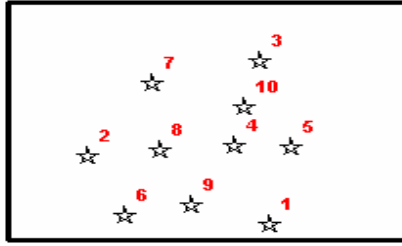
Snapshot GIS Layer 1999

| OBJECTID | TYPE | ID | T_1999 |
|----------|----------|-----|--------|
| 1 | Portable | 14 | 1 |
| 2 | Portable | 94 | 1 |
| 3 | Portable | 289 | 1 |
| 4 | Portable | 311 | 1 |
| 5 | Portable | 346 | 1 |
| 6 | Portable | 347 | 1 |
| 7 | Portable | 348 | 1 |
| 8 | Portable | 406 | 1 |

Figure 2.11: Snapshot Spatial Data after Tuple Time-stamping

and “T_1999”. Tuple values for the fields are “1”, indicating the existence or validity for the tuples.

The notion of object time-stamping appears for object-relational DBMSs (and for object-oriented DBMSs). Object time-stamping in most cases is akin to tuple time-stamping. The object state is stored in a relational table as a record containing atomic or complex attributes. When an STComposite GIS layer is generated from snapshot GIS layers, the smallest spatial units of the STComposite GIS layers, namely, STComposite objects, carry time-stamps. Figure 2.12 presents an STComposite GIS layer derived from the snapshot GIS layers in Figure 2.11. The STComposite GIS layer consists of every point that existed in 1994, 1996, or 1999. Its relational table keeps records with a “1” indicating the existence of an STComposite object in a particular year and a “0” otherwise. For example, a point with OBJECTID 1, 2, 3, 4, and 5 existed in 1994, 1996, and 1999 (indicated as gray rows in Figure 2.11 and Figure 2.12), while OBJECTID 6, 7, and 8 only existed in 1999 (green rows in Figure 2.11 and Figure 2.12), and OBJECTID 9 and 10 existed in 1996 (yellow rows in Figure 2.11 and Figure 2.12). Note that attributes from snapshot GIS layers in 1994, 1996, and 1999 are also included in the STComposite relational table. The example shown in Figure 2.12 is for points. A further implementation of the STComposite GIS layer from snapshot GIS layers of other feature types is presented in Chapter 5.



STComposite GIS Layer

| OBJECTID | TYPE_T1994 | TYPE_T1996 | TYPE_T1999 | ID_T1994 | ID_T1996 | ID_T1999 | T1994 | T1996 | T1999 |
|----------|------------|------------|------------|----------|----------|----------|-------|-------|-------|
| 1 | Portable | Portable | Portable | 14 | 14 | 14 | 1 | 1 | 1 |
| 2 | Portable | Portable | Portable | 94 | 94 | 94 | 1 | 1 | 1 |
| 3 | Portable | Portable | Portable | 289 | 289 | 289 | 1 | 1 | 1 |
| 4 | Portable | Portable | Portable | 311 | 311 | 311 | 1 | 1 | 1 |
| 5 | Portable | Portable | Portable | 346 | 346 | 346 | 1 | 1 | 1 |
| 6 | | | Portable | | | 347 | 0 | 0 | 1 |
| 7 | | | Portable | | | 348 | 0 | 0 | 1 |
| 8 | | | Portable | | | 406 | 0 | 0 | 1 |
| 9 | Portable | | | 313 | | | 1 | 0 | 0 |
| 10 | Portable | | | 374 | | | 1 | 0 | 0 |

Figure 2.12: STComposite Spatial Data after Object Time-stamping

2.4 Summary

There are many problems associated with spatio-temporal data models. This chapter briefly covers several essential concepts closely related to the Transland spatio-temporal data model. These will be expounded upon in the next several chapters. While reviewing spatial data models used in GIS applications, this chapter actually identifies differences between data models and DBMSs. The description of spatial data models accompanied with the development of DBMSs indicates that spatial data models with rich data types and relational query operations, developed within object-relational DBMSs, are good candidates to handle time-varying spatial data. The release of the ArcGIS data model with its ArcObjects COM development environment, as an object-

relational spatial data model, facilitates the addition of temporal data to spatial data models. Furthermore, its use leads to recognition that the Transland spatio-temporal data model is to be built upon well-developed spatial data model technology. This chapter then proceeds to explore methods about tuple and object time-stamping where time is combined with spatial data to construct spatio-temporal data. One spatio-temporal data type is called STComposite data, which can be generated from time-stamped snapshot spatial data.

Different from a generic data model, the Transland spatio-temporal data model has a problem domain that is relevant to land use-transportation interaction, and, in particular, spatial and temporal patterns of that interaction. The next chapter will cover this problem domain and attempt to represent the interaction with the key components of a spatio-temporal data model.

3 EXPLORATORY DATA ANALYSIS OF LAND USE- TRANSPORTATION INTERACTION WITH A SPATIO- TEMPORAL DATA MODEL

Transportation planners have treated land use and transportation as a crucial research subject for several decades. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 required that “transportation plans must take into account the likely effect of transportation policy decisions on land use and development and the consistency of transportation plans and programs with land use and development plans.” (Miller, et al., 1999, p.3). The transportation Equity Act for the 21st Century (TEA-21) Act of 1998, which succeeds the ISTEA act, also recognizes the land use and transportation relationships within a broader context of economic development and environmental issues. In addition, both ISTEA and TEA-21 require transportation plans to conform to the requirements of the Clean Air Act Amendments (CAAA) of 1990. Recognizing the inadequacy of existing models to address the legislative requirements, the U.S. Department of Transportation and the U.S. Environment Agency jointly established a Travel Model Improvement Program (TMIP) in 1993. The TMIP includes six tracks. One of the tracks focuses on improving modeling capabilities and data for integrated analysis of land use and transportation interaction, while the other tracks investigate the relationships between transportation and air quality (Miller, et al., 1999).

Most land use and transportation interaction studies take a confirmatory analysis approach that is based on prior theories or mathematical models. These studies certainly have helped establish theoretical bases and solution methods in our attempts to gain a

better understanding of land use and transportation interaction. However, the literature suggests that little consensus regarding the conclusions can be drawn from empirical studies that apply these models (Guiliano, 1995). The inconsistent findings from the literature also suggest the existence of significant spatial and temporal variations between different geographic areas. For example, Guiliano (1995) reviews several empirical studies and reports that rail transit systems have no systematic influence on urban structures between different cities in the United States and Canada. Even in the same city, land development occurred near some rail stations but not around other stations. In addition, she referenced a beltway study of 54 U.S. cities (27 with beltways) and pointed out that, while portions of a beltway in each metropolitan area experienced significant development, other portions underwent insignificant or no changes (Payne-Maxie Consultants, 1980).

Land use and transportation system changes take place in a highly dynamic environment that involves many forces such as economic development, population growth, and policy decisions. Models built on a confirmatory analysis approach are often based on a pre-specified spatial and temporal scale; therefore, they are less flexible of examining the dynamic nature of various forces acting at different spatial and temporal scales on land use and transportation interaction. *Exploratory data analysis* (EDA), on the other hand, takes a speculative and systematic approach to assist us in searching for patterns and processes hidden in the data sets (Openshaw, 1994; Goodchild, 2000). EDA emerged in the 1970s as methods were developed for revealing what would otherwise go

unnoticed with the use of standard statistical analysis (Tukey, 1977). The GIS research community began to develop methods for exploratory spatial data analysis in the 1980s.

The main challenges of integrating EDA with GIS are to develop methods of sifting through large spatial data sets and to design visualization tools of presenting the patterns and relationships hidden in the large data volume. Visual data analysis of examining maps to search for hidden patterns and relationships is a useful form of spatial analysis (Goodchild, 2000). EDA does not impose scale-specific assumptions on the analysis procedures; therefore, patterns and relationships can emerge from the analysis rather than be imposed under a confirmatory data analysis approach. In recent years, use of EDA with GIS has been actively pursued in spatial data mining and spatial knowledge discovery (e.g., Miller and Han, 2001).

GIS by design are rich in spatial analysis and visualization functions. Various analysis and modeling procedures have been applied to GIS for Transportation (GIS-T). Many of the GIS-T applications are good candidates for EDA within a GIS environment. For example, we could explore spatio-temporal traffic accident patterns using traffic accident data (e.g., accident type, vehicle type, driver characteristics, time in a day) with GIS layers of highway characteristics (e.g., speed limit, pavement condition, curvature, lighting) and environmental data (e.g., weather, terrain). For studies of land use and transportation interaction, spatial analysis and visualization functions in a GIS coupled with an EDA approach will allow analysts to examine the different patterns caused by

various forces related to land use and transportation changes between urban areas, as well as their effects at different spatial and temporal scales within a specific urban area.

Specifically, a GIS-based exploratory spatial analysis system for land use and transportation interactions should meet the following objectives:

- (1) The system must include spatio-temporal databases that allow investigation of land use and transportation interaction at different temporal scales (i.e., short-term and long-term effects of land use and transportation interaction).
- (2) The system must permit analysts to investigate relationships among all GIS map layers that represent the various forces (e.g., population growth, economic development, transportation investments) underlying the process of land use and transportation interaction at different spatial scales for various periods.
- (3) The system must provide methods for a systematic exploration of relevant data sets and transportation interaction patterns.

Such a GIS-based exploratory analysis does not replace the existing confirmatory modeling approaches. Instead, it serves as a complement to the confirmatory analysis approach. Findings from the GIS-based exploratory analysis system can be used to revisit the existing model structures or to validate the model parameters for a particular study area. They also may suggest new hypotheses for researchers to examine hidden spatio-temporal patterns of land use and transportation interaction.

This chapter aims at meeting the above objectives by identifying six scenarios that transportation planners are likely to use to explore spatio-temporal data changes for analyzing land use and transportation interaction. The chapter first presents theoretical and empirical conclusions drawn from previous research on land use-transportation interaction. It then describes the six scenarios in correspondence with the theoretical and empirical considerations.

3.1 Theoretical and Empirical Considerations of Land Use-Transportation Interaction

It is common wisdom among transportation planners that urban land use and transportation are closely linked. There have been a number of studies that identify links between transportation projects and land developments. With respect to theoretical and empirical considerations, these studies examine the land use developments (Cosby and Buffington, 1978a and 1978b; Payne-Maxie Consultants, 1980; Buffington, et al., 1985; Hirschman and Henderson, 1990), property values (Boyce, 1972; Lerman, et al., 1978; Huang, 1994 and 1996; Ryan, 1999; Vadali and Sohn, 2001), location choice (Cascetta, et al., 2000; Kawamura, 2001), and improved accessibility (Martinez, 1995; Ryan, 1999). The theoretical considerations entail the expected impacts of essential factors such as urban density, employment density, neighborhood design, location, city size, accessibility, travel cost and travel time. Results from empirical studies of land use-transportation interaction verify the expectations derived from theoretical insights.

3.1.1 Theoretical Findings

Table 3.1 illustrates the impact of land use development on transportation spatial and temporal patterns from a theoretical point of view. The impact of high residential density in reducing average trip length is likely to be minimal in the absence of travel cost increases, whereas a high density of employment is positively correlated with average trip length. Attractive neighborhood facilities can be seen as a “pull” factor for reducing trip length. With regard to trip frequency little or no impact is to be expected from land use development. Residential and employment density as well as large agglomeration size and good public transportation accessibility of a location tend to be positively correlated with the modal share of public transportation, while neighborhood design and a mixture of workplaces and residences with shorter trips are likely to have a positive impact on the share of cycling and walking.

Table 3.2 illustrates the impact of transportation projects on land use. The impact of transportation on land use is mediated by a change in the accessibility of a location. Higher accessibility increases the attractiveness of a location for land uses thus influencing the direction of new urban development. If, however, accessibility in an entire city is increased, it will result in a more dispersed settlement structure. In general, the theoretical considerations support the conclusion that the impact of “pull” measures, i.e. land use measures, is much weaker than the impact of “push” measures, i.e. decreases in travel time, travel cost, etc.

Table 3.1: Theoretically Expected Impact of Land Use (Source: European Commission in Transport Sector (DG VII), 1999)

| Direction | Factor | Impact on | Expected impacts |
|----------------------------|----------------------|----------------|---|
| Land use ↓ Transport | Residential density | Trip length | Higher residential density alone will not lead to shorter trips. A mixture of workplaces and residences can lead to shorter trips if travel costs are increased. |
| | | Trip frequency | Little impact expected. If trips are shorter, more trips may be made. |
| | | Mode choice | Minimum residential densities are a prerequisite for efficient public transport. More walking and cycling trips will be made only if trips become shorter (see above). |
| | Employment density | Trip length | Concentration of workplaces in few employment centres tends to increase average trip lengths. A balance of workplaces and residences in an area would lead to shorter work trips only if travel becomes more expensive. |
| | | Trip frequency | Little impact expected. If trips are shorter, more trips may be made. |
| | | Mode choice | Concentration of workplaces in few employment centres may reduce car use if supported by efficient public transport. More walking and cycling trips will be made only if trips become shorter (see above). |
| | Neighbourhood design | Trip length | Attractive public spaces and a variety of shops and services can induce more local trips. |
| | | Trip frequency | If trips are shorter, more trips may be made. |
| | | Mode choice | Street layout, pedestrian spaces and cycling lanes could lead to more walking and cycling. |
| | Location | Trip length | More peripheral locations tend to have longer trips. |
| | | Trip frequency | No impact expected. |
| | | Mode choice | Locations close to public transport stations should have more public transport trips. |
| | City size | Trip length | Trip length should be negatively correlated with city size. |
| | | Trip frequency | No impact expected. |
| | | Mode choice | Larger cities can support more efficient public transport systems, so more trips should be made by public transport in larger cities. |

Table 3.2: Theoretically Expected Impact of Transportation (Source: European Commission in Transport Sector (DG VII), 1999)

| Direction | Factor | Impact on | Expected impacts |
|----------------------------|---------------|----------------------|---|
| Transport ↓ Land use | Accessibility | Residential location | Locations with better accessibility to workplaces, shops, education and leisure facilities will be more attractive for residential development, have higher land prices and be developed faster. Improving accessibility locally will change the direction of new residential development, improving accessibility in the whole urban area will result in more dispersed residential development. |
| | | Industrial location | Locations with better accessibility to motorways and railway freight terminals will be more attractive for industrial development and be developed faster. Improving accessibility locally will change the direction of new industrial development. |
| | | Office location | Locations with better accessibility to airports, high-speed rail railway stations and motorways will be more attractive for office development, have higher land prices. Improving accessibility locally will change the direction of new office development. |
| | | Retail location | Locations with better accessibility to customers and competing retail firms will be more attractive for retail development, have higher land prices and be faster developed. Improving accessibility locally will change the direction of new retail development. |

3.1.2 Empirical Findings

Table 3.3 describes the impact of land use development on transportation spatial and temporal patterns. Residential density has been shown to be inversely related to trip length. Centralization of employment results in longer trips, while trip lengths are shorter in areas with a balanced residents-to-workers ratio. Studies confirm that attractive neighborhood facilities also contribute to shorter average trip lengths. The theoretical insight that distance of residential locations to employment centers is an important determinant of average trip length has been confirmed empirically. None of the studies

Table 3.3: Impacts of Land Use in Empirical Studies (Source: European Commission in Transport Sector (DG VII), 1999)

| Direction | Factor | Impact on | Observed impacts |
|----------------------------|----------------------|----------------|--|
| Land use ↓ Transport | Residential density | Trip length | Numerous studies support the hypothesis that higher density combined with mixed land use leads to shorter trips. However, the impact is much weaker if travel cost differences are accounted for. |
| | | Trip frequency | Little or no impact observed. |
| | | Mode choice | The hypothesis that residential density is correlated with public transport use and negatively with car use is widely confirmed. |
| | Employment density | Trip length | In several studies the hypothesis was confirmed that a balance between workers and jobs results in shorter work trips, however this could not be confirmed in other studies. Mono-functional employment centres and dormitory suburbs, however, have clearly longer trips. |
| | | Trip frequency | No significant impact was found. |
| | | Mode choice | Higher employment density is likely to induce more public transport use. |
| | Neighbourhood design | Trip length | American studies confirmed that 'traditional' neighbourhoods have shorter trips than car-oriented suburbs. Similar results are found in Europe. |
| | | Trip frequency | No effects are reported. |
| | | Mode choice | 'Traditional' neighbourhoods have significant higher shares of public transport, walking and cycling. However, design factors lose in importance once socio-economic characteristics of the population are accounted for. |
| | Location | Trip length | Distance to main employment centres is an important determinant of distance travelled. |
| | | Trip frequency | No effect observed. |
| | | Mode choice | Distance to public transport stops strongly influences public transport use. |
| | City size | Trip length | Mean travel distances are lowest in large urban areas and highest in rural settlements. |
| | | Trip frequency | No effect observed. |
| | | Mode choice | Public transport use is highest in large cities and smallest in rural settlements. |

reported a significant impact of any factor on trip frequency. Residential and employment density as well as large agglomeration size and rapid access to public-transport stops of a location were found to be positively correlated with the modal share of public transport. “Traditional” neighborhoods showed a higher share of non-car modes.

Table 3.4 illustrates the impact of transportation projects on land use.

Accessibility is reported to be of varying importance for different types of land uses. It is an essential location factor for retail, office and residential uses. Locations with high accessibility tend to be developed faster than other areas. The value of accessibility to manufacturing industries varies considerably depending mainly on the goods produced. In general, ubiquitous improvements in accessibility invoke a more dispersed spatial organization of land uses.

Table 3.4: Impacts of Transportation in Empirical Studies (Source: European Commission in Transport Sector (DG VII), 1999)

| Direction | Factor | Impact on | Observed impacts |
|----------------------------|---------------|----------------------|---|
| Transport ↓ Land use | Accessibility | Residential location | More accessible locations are developed faster. If accessibility in the whole region grows, residential development will be more dispersed. |
| | | Industrial location | There is little evidence of impacts of accessibility on location of manufacturing, but ample evidence of the importance of accessibility for high-tech and service firms. |
| | | Office location | Office development occurs predominantly at highly accessible inner-city locations or in office parks or 'edge cities' at the urban periphery with good motorway access. |
| | | Retail location | Retail development occurs either at highly accessible inner-city locations or on peripheral sites with ample parking and good road accessibility. |

3.2 A Framework of Transland Scenarios

Like many spatial processes, the interaction of land use and transportation discussed above involves a time element (when), a location element (where), and an attribute element (what) that are interrelated to each other. Sinton (1978) suggested a measurement framework of using the three main components (i.e., location, time and attribute) to serve as the “fix”, the “control”, and the “measure” parameters when performing a measurement. Each of the three components can serve as the “fix”, the “control”, or the “measure” parameter in a measurement. It therefore results in a total of six possible measurement scenarios (Table 3.5). Each of the six measurement scenarios is suitable for a particular type of analysis need. For example, we could “fix time” (say, April 1, 2001) and “control location” (say, 0.5-mile, 1-mile, and 1.5-mile buffer zones around the interchanges of I-75 in Broward County, FL) to “measure attributes” (say, land use types). Application of this measurement scenario #3 (Table 3.5) will provide us with the land use information within the buffer zones of the interchanges of I-75 in Broward County on the chosen date. Alternatively, we could “fix attribute” (say, average daily traffic count higher than 10,000) and “control time” (say, Year 1990 through Year 2000) to “measure locations” (e.g., highway segments or traffic count stations). Measurements from this scenario #6 offer the information to answer a different type of question.

Sinton’s measurement framework is based on the proposition that location, time and attribute are three separable components so that it is easier to measure one

Table 3.5: Sinton’s Measurement Framework

| | Fixed Component | Controlled Component | Measured Component |
|------------|-----------------|----------------------|--------------------|
| Scenario 1 | Location | Time | Attribute |
| Scenario 2 | Location | Attribute | Time |
| Scenario 3 | Time | Location | Attribute |
| Scenario 4 | Time | Attribute | Location |
| Scenario 5 | Attribute | Location | Time |
| Scenario 6 | Attribute | Time | Location |

component by fixing and controlling the other two. Conventional snapshot-based GIS, which represent data for each GIS layer at a given point in time, correspond to a subset of Sinton’s measurement framework. A raster GIS implementation of the snapshot approach is equivalent to scenario 3 in Sinton’s framework that fixes time and controls locations (i.e., pre-determined cell size) to measure attributes (e.g. land use types). A vector snapshot GIS implementation, on the other hand, fixes the time and controls attributes (e.g., land use types) to measure their locations (i.e., boundaries of land use zones). This follows scenario 4 of Sinton’s measurement framework. Under either implementation, transportation planners can answer questions such as “where were residential or commercial land use zones in 2000?” using the query functions in a GIS.

The snapshot GIS approach, however, is ineffective in dealing with the other four scenarios in Sinton’s measurement framework. For instance, scenario 1 measures attribute changes (e.g., land use changes) over a controlled time period (e.g., 1980 through 2000) at a fixed location. Since each snapshot GIS stores data for a given time point in a separate layer and does not explicitly handle the temporal relationships among the layers, we must perform overlay analyses of all GIS layers covering the specified

time period repeatedly in order to find out, for example, the land use changes during the 1980-2000 period. To overcome this shortcoming, spatio-temporal data models that extend the static snapshot GIS approach need to be developed. The design of the Transland spatio-temporal data model in this dissertation adapts the space-time composite concept and extends it to incorporate the semantic concept and the object identity concept with time-based object classes that track the change history of vector GIS data.

In addition to the design of the Transland spatio-temporal data model, another main challenge is to design a systematic method for exploration of various data sets relevant to land use and transportation interaction. As mentioned above, Sinton's measurement framework focuses on the measurements of a single phenomenon. When we need to examine the interaction between two phenomena (i.e. land use system and transportation system), it is necessary to extend this framework. By fixing one of the three components, controlling another component, and measuring the third component, it allows us to explore the effects of various forces interacting between the two systems over time.

Table 3.6 shows a proposed Transland spatio-temporal interaction framework with six scenarios for exploring land use and transportation interaction. In this framework, all data related to the land use system and the transportation system are stored with their respective spatial, attribute, and temporal elements. Since all spatial or attribute changes in either system and between the two systems take place over time, we therefore use time as the key component to facilitate spatio-temporal analysis of land use

Table 3.6: Transland Scenarios

| | Fixed Component | Controlled Component | Measured Component |
|------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Scenario 1 | Transportation (Space-Attribute) | Land Use (Space-Attribute) | Time |
| Scenario 2 | Transportation (Space-Attribute) | Time | Land Use (Space-Attribute) |
| Scenario 3 | Time | Transportation (Space-Attribute) | Land Use (Space-Attribute) |
| Scenario 4 | Time | Land Use (Space-Attribute) | Transportation (Space-Attribute) |
| Scenario 5 | Land Use (Space-Attribute) | Transportation (Space-Attribute) | Time |
| Scenario 6 | Land Use (Space-Attribute) | Time | Transportation (Space-Attribute) |

and transportation interaction. The three components (spatial, temporal, and time) can be accessed either separately or in combinations via custom user interfaces. Six scenarios are derived from the permutation of the three components. They are used to measure either spatial or temporal patterns of the interaction between land use development and transportation projects, as addressed in previous sections. The spatial patterns are the changes of land use/transportation factors over geographic space at the same timeframes when the land use and transportation interact (scenarios 3 and 4 in Table 3.6). In a different way that explicitly reveals timeframes for the interaction between land use and transportation, the temporal patterns allow users to define timeframes for the interaction when it changes over the space. Two different types of temporal patterns can be derived by controlling time constraints. Constrained temporal patterns specifically define timeframes (e.g., since 1995) as the controlled factor (scenarios 2 and 6) while non-constrained temporal patterns leave timeframes as the measured factor (scenarios 1 and 5).

3.3 Descriptions of the Transland Scenarios

An exploratory analysis of spatial and temporal patterns of land use-transportation interaction is a major theme in Section 3.1 with respect to their theoretical and empirical considerations. Although the land use-transportation interaction reported in the literature involves many factors, Section 3.2 categorizes them into six scenarios. This section presents the details of the six scenarios by exemplifying them according to the land use-transportation impact studies in Section 3.1. Each scenario also describes a Graphic User Interface (GUI).

3.3.1 Scenario 1

Scenario 1 identifies the timeframes (i.e., measured component) of which a transportation project (i.e., fixed component) has on different land use types and their locations (i.e., controlled component). Sample queries under this scenario include:

- 1) When did different land developments in the region respond to the improvement of accessibility due to the I-595 construction project?
- 2) What was the temporal evolution of residential land-use changes in response to the I-595 construction?

An attempt to find out a solution for the first question recognizes “I-595 construction project” as a fixed component, with “land use development” as a controlled component and “when” as a measured component as shown in Table 3.7.

Table 3.7: Scenario 1 Components

| Fixed component | Controlled component | Measured component |
|----------------------------------|---|--------------------|
| Transportation (Space-Attribute) | Land use (Space-Attribute) | Time |
| I-595 construction project | Land developments in the region of I-595 construction project | When |

The scenario can be implemented through a GUI. The GUI equipped with spatial query and analytical functions is capable of handling cases that involve time-varying spatial data.

Step 1: The user selects a transportation project. The system displays the location, temporal and attribute information of the transportation project.

Step 2: The user specifies a spatial extent (i.e., a search distance) and a land use change type (e.g., changes to residential land use type) around the selected transportation project.

Step 3: The system will report the years when the user-specified land use change took place within the search extent for all of the years with valid land use data. The system also can retrieve the user-specified land use characteristics within the specified spatial extent. The locational and temporal land use changes can be presented as maps showing when and where land-use changes appeared in the region.

Step 4: Steps 2 and 3 can be repeated for the different land use development.

3.3.2 Scenario 2

Scenario 2 allows users to identify the land use changes (i.e., measured component) that are associated with a transportation improvement project (i.e., fixed component) had during different timeframes (i.e., controlled component). Sample queries under this scenario include:

- 1) Where were the areas that experienced greater than 20% land value increases since 1995 due to the construction of the I-595?
- 2) Where were the new residential land use zones that occurred during the five years after the construction of I-595?

Similar to scenario 1, “I-595 construction project” acts as the fixed component. In contrast to scenario 1, “since 1995” is now the controlled component and “where are areas that experience greater than 20% land value” as the measured component (see Table 3.8).

A GUI with the following steps describes what is necessary for answering the questions from scenario 2.

Table 3.8: Scenario 2 Components

| Fixed component | Controlled component | Measured component |
|----------------------------------|----------------------|---|
| Transportation (Space-Attribute) | Time | Land use (Space-Attribute) |
| I-595 construction project | since 1995 | Where are areas that experience greater than 20% land value increases |

- Step 1: The user selects a transportation project. The system displays the location, temporal and attribute information of the transportation project.
- Step 2: The user specifies a spatial extent (i.e., a search distance) and a land use change type (e.g., changes to residential land use type) around the selected transportation project.
- Step 3: The system will report a list of timeframes for land use data within the spatial extent. The user then specifies a timeframe for analysis.
- Step 4: The system reports the land use data according to the timeframe specified in Step 3.
- Step 5: Steps 3 and 4 are repeated for the different user-specified timeframes.

3.3.3 Scenario 3

Scenario 3 identifies the land use changes (i.e., measured component) due to different transportation improvement projects (i.e., controlled component) at a selected time (i.e., fixed component). Sample queries under this scenario include:

- 1) What was the land-use pattern around major transportation projects in 1996?
- 2) Where were the vacant land parcels within a 1-mile zone of an ongoing transportation project in 1996?

This is a snapshot scenario, which at the very beginning defines a timeframe as the fixed component. As shown in Table 3.9, this timeframe will determine when the

Table 3.9: Scenario 3 Components

| Fixed component | Controlled component | Measured component |
|-----------------|-------------------------------------|-------------------------------|
| Time | Transportation (Space-Attribute) | Land use (Space-Attribute) |
| 1996 | Major transportation projects | Land use patterns |

controlled component “major transportation projects” and the measured component “land use patterns” occur (as shown below to illustrate the first question).

To support this scenario, it is necessary to develop a GUI that assists users with the following steps:

Step 1: The user selects a timeframe (e.g., 1996).

Step 2: The system automatically identifies transportation projects that are related to the timeframe specified in Step 1. The user selects transportation projects for analysis.

Step 3: For each user-selected transportation project, the system identifies land use development with a certain search distance from the selected transportation project and reports the land use data according to the user-specified timeframe.

Step 4: Steps 2 and 3 are repeated for the different user-specified transportation projects.

3.3.4 Scenario 4

Scenario 4 allows users to identify the transportation patterns (i.e., measured component) due to different land use development (i.e., controlled component) at a selected timeframe (i.e., fixed component). Sample queries under this scenario include:

- 1) What were the traffic volumes on major roads in traffic analysis zones (TAZs) with population density higher than 3,000 persons per square mile in 1996?
- 2) Which road segments in Broward County adjacent to commercial land use in 1998 experienced a level of service of D?

Like scenario 3, this is another snapshot scenario. For the first question, “TAZs with population density higher than 3,000 square miles” becomes the controlled component and “Traffic volumes on major roads” the measured component (see Table 3.10).

To support this scenario, a GUI is developed with the following steps:

Step 1: The user selects a timeframe.

Step 2: The system automatically identifies land use development that is related to the timeframe specified in Step 1.

Step 3: For each land use development, the system identifies transportation projects with a certain search distance from the selected land use development and reports the transportation data according to the user-specified timeframe.

Step 4: Steps 2 and 3 are repeated for the different user-specified land use development.

Table 3.10: Scenario 4 Components

| Fixed component | Controlled component | Measured component |
|-----------------|--|---|
| Time | Land Use (Space-Attribute) | Transportation (Space-Attribute) |
| 1996 | CENSUS tracts with population density higher than 3,000 square miles | Traffic volumes on major roads in TAZs |

3.3.5 Scenario 5

Scenario 5 helps users to identify the timeframes (i.e., measured component) during which a land use pattern (i.e., fixed component) corresponded with different transportation components (i.e., controlled component). Sample queries under this scenario include:

- 1) When did major transportation projects take place in TAZs with an employment density higher than 8,000 per square mile?
- 2) What was the temporal evolution of traffic volumes on major roads in response to a major land development project?

Scenario 5 is paired with scenario 1 because these two scenarios have the same measured component – the temporal component. Taking the first question as an example, this scenario treats “TAZs with employment densities higher than 8,000 per square mile” as the fixed component and “major transportation projects” as the controlled component (see Table 3.11).

Table 3.11: Scenario 5 Components

| Fixed component | Controlled component | Measured component |
|--|--|--------------------|
| Land use (Space-Attribute) | Transportation (Space-Attribute) | Time |
| Census tracts with employment densities higher than 8,000 per square mile | Major transportation projects in TAZs | When |

To support this scenario, a GUI assists users as below:

Step 1: The user selects a land use development (e.g., TAZs with an employment density of more than 8000 per square mile). The system displays the location of the selected land use development.

Step 2: The user specifies a spatial extent (i.e., a search distance) around the selected land use development.

Step 3: The system will report the years when the user-specified transportation data took place within the search extent for all of the years with valid transportation data. The locational and temporal transportation system changes can be presented as maps showing when and where transportation changes appeared in the region(s).

Step 4: Steps 2 and 3 are repeated for different user-specified spatial extents and transportation characteristics.

3.3.6 Scenario 6

Scenario 6 identifies the transportation system changes (i.e., measured component) of which a land use pattern (i.e., fixed component) had during different timeframes (i.e., controlled component). Sample queries under this scenario include:

- 1) Where were the new transportation improvement projects during the five years after the construction of a major shopping mall?
- 2) Which road segments experienced greater than 20% traffic volume increases in a 3-year period since traffic analysis zones reached a population density of 5,000 per square mile?

Scenario 6 is paired with scenario 2 because these two scenarios secure the same controlled component, time. For the first question, this scenario treats “The construction of a major shopping mall” as the fixed component and “ transportation improvement projects” as the measured component (see Table 3.12).

To support this scenario, a GUI assists users below:

Step 1: The user selects a land use development. The system enables the users to define its location, temporal and attribute information.

Step 2: The user specifies a spatial extent (i.e., a search distance) and a transportation change type around the selected land use development.

Step 3: The system will list the years in association with transportation data within the specified spatial extent of the land use development. The user then specifies a timeframe.

Step 4: The system reports the transportation data according to the timeframe specified in Step 3. Users can use the data to examine the spatial and temporal changes of transportation patterns.

Step 5: Steps 3 and 4 are repeated for the different user-specified timeframes.

Table 3.12: Scenario 6 Components

| Fixed component | Controlled component | Measured component |
|---|------------------------|-------------------------------------|
| Land use (Space-Attribute) | Time | Transportation (Space-Attribute) |
| The construction of a major shopping mall | During last five years | Transportation improvement projects |

3.4 Summary

This chapter introduces the Transland scenario framework based on the theoretical and empirical considerations of land use-transportation interactions. In comparison with Sinton's measurement framework, the Transland scenario framework identifies the time component along with the land use and transportation components. Three components are chosen to form the Transland scenarios that can identify the spatial and temporal patterns of land use-transportation interaction. The Transland scenarios are actually a list of questions that are relevant to the spatial and temporal patterns. Questions from the temporal patterns also vary according to whether they measure the time component or control the time component. The six scenarios cover a wide range of possible queries related to spatial and temporal patterns of land use-transportation interaction. They can be implemented as GIS GUIs with the support of the Transland spatio-temporal data model, which is to be discussed in the next two chapters with respect to its design and implementation.

4 THE DESIGN OF THE TRANSLAND SPATIO-TEMPORAL DATA MODEL WITH OBJECT-ORIENTED ANALYSIS AND DESIGN (OOA&D)

The proposed spatio-temporal interaction framework in Chapter 3 provides a systematic and flexible design for transportation planners to explore land use and transportation interactions. The framework is capable of exploring spatial and attribute changes between the land use and transportation components over time. It is also flexible enough to examine “when” changes take place by fixing and controlling the spatial and attribute data of land use and transportation components respectively.

Most GIS packages today already provide powerful functions of handling spatial and attribute data in an integrated environment. The dissertation takes an approach to extending an existing commercial GIS package to incorporate temporal data in the design of the Transland spatio-temporal data model for exploratory analysis of land use and transportation interaction. Whenever the existing GIS capabilities can help accomplish specific tasks, they are used in the data model design. This chapter will use an Object-Oriented Analysis and Design (OOA&D) method for the design of the Transland spatio-temporal data model. The following sections will first introduce the concepts of OOA&D along with its design tool -- Unified Modeling Language (UML). Then, the ArcGIS data model, released as an OOA&D by ESRI, is introduced as an existing spatial data model that provides spatial objects. Finally, the chapter proposes Transland spatio-temporal objects. They are extended from the spatial objects of ArcGIS spatial objects

and serve as a basis for composing the scenarios of the spatio-temporal interaction framework.

4.1 Object-oriented Analysis & Design (OOA&D) for Spatial Data Models

Currently available GIS database technology, such as the ESRI ArcGIS data model, provides users with a method to design a spatial data model based on object-oriented concepts. For example, it is feasible to define objects as they exist in the real world and the relationships between the classes. Instead of using generic geometric features (i.e., points, lines and polygons) to represent different kinds of real world entities, the data model now can define a traffic count station feature class or a traffic analysis zone feature class in a geodatabase. The data model also can define transportation projects as a separate class (i.e., a semantic object) and then create a relationship class to link each transportation project to its related street segments.

There are several ongoing efforts to develop spatial data models with OOA&D. Examples include the ArcGIS Land Parcel Data Model (Meyer, et al., 2001) and the ArcGIS Transportation Data Model (Curton, et al., 2001) from ESRI; the Transportation Object Platform (TOP) for intelligent management of multi-modal network data by ScanRail Consult in Denmark (Atkins Transportation Scandinavia, Denmark); and a multidimensional data model incorporating the time dimension to extend the LRS data model for transportation location referencing systems (Koncz and Adams, 2001).

With the development of an object-oriented method for the design of spatial data models, it is now feasible for OOA&D to define objects and their relationships that are specific and intuitive to a particular application domain. For example, it is more intuitive and useful for transportation planners to deal with objects such as roads, bridges, transit stations and traffic accidents instead of the geometric features such as points, lines and polygons in a GIS. The spatial data models built with OOA&D offer valuable guidelines on the design of the Transland spatio-temporal data model. Among them, the ArcGIS parcel and transportation data models provide templates for managing land use and transportation data. ArcGIS Parcel and Transportation Data Models define basic land use and transportation classes and their relationships. The Transland spatio-temporal data model can modify them to include additional classes, properties and relationships to support specific applications.

4.1.1 Unified Modeling Language (UML)

OOA&D allows software developers to decompose a complex real world system into a set of diagrams to represent its processes, classes and other relationships. These diagrams serve as useful information in a database design process. A number of OOA&D methods have been proposed in the literature (e.g., Chen, 1991; Booch, et al., 1999). These OOA&D methods are collectively known as the computer-assisted software engineering (CASE) tools. One problem with the various OOA&D methods was the different notations used in the diagrams to represent a real world system. In

1997, the Unified Modeling Language (UML) was adopted by the Object Management Group and became an industry standard.

UML is a graphic modeling language rather than a programming language. It consists of object-oriented analysis and design notations that can be used for everything from high-level analysis concepts down to very detailed design elements (Richter, 1999). A set of diagrams defined with UML notations can describe real world activities and represent their concepts and relationships. Among the various UML diagrams, class diagrams are the most critical for data model design. UML class diagrams translate real world objects into software entities with attributes, associations, methods, interfaces and dependencies.

Two examples are provided below to illustrate some basic UML notations. Figure 4.1 shows a class hierarchy for defining different types of semantic classes. It starts with the top box (ESRI object class), which is an ArcGIS 8 predefined object type. From this ESRI class, a subclass of SemanticObjectTable is defined to inherit the properties and behaviors of its parent class (i.e., ESRI object class) along with additional attributes specific to the SemanticObjectTable class (i.e., ScenarioCode and FileLocation). TransportationSemantic and LandUseSemantic are two subclasses that inherit from the SemanticObjectTable class. Again, additional attributes can be defined for each of these subclasses. This inheritance hierarchy allows users to define specific classes based on a parent ESRI class.

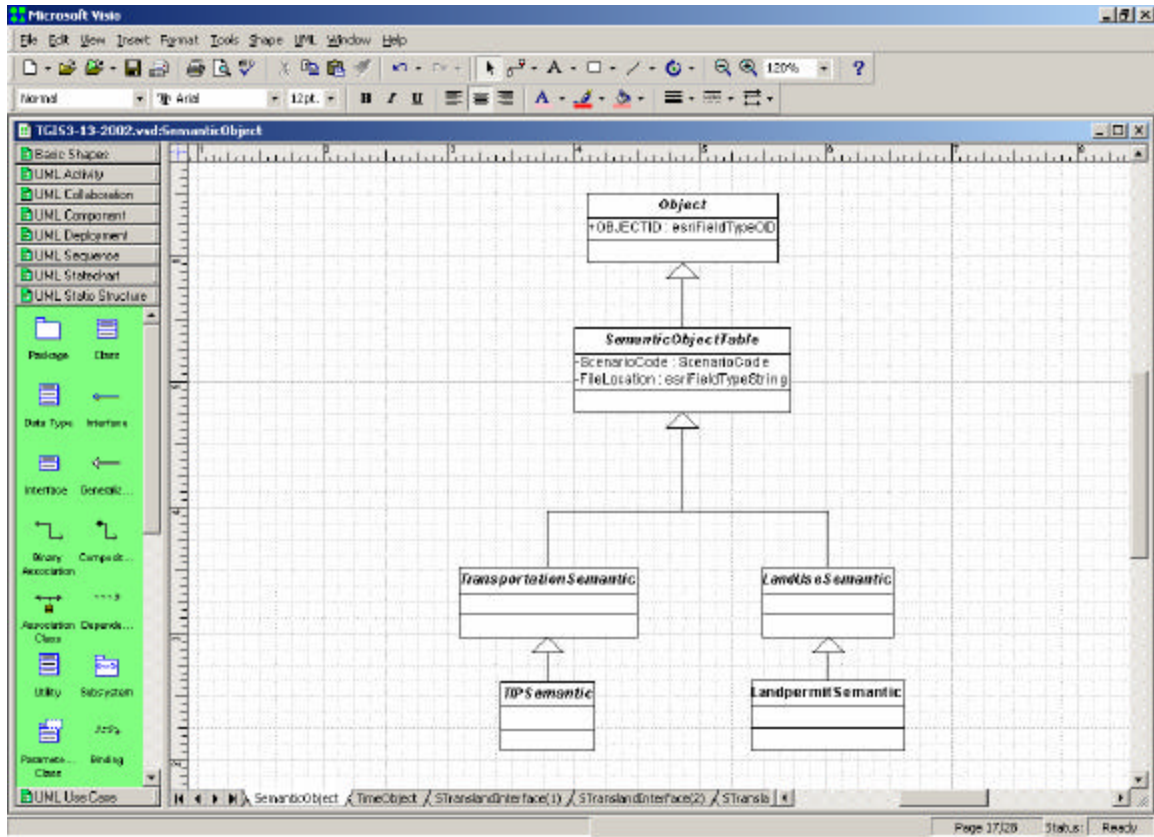


Figure 4.1: An UML Example for Classes

Figure 4.2 shows a UML example of relationships between classes. The possible cardinality (also known as multiplicity) at each end of an association between two classes may be one and only one (1), zero or one (0..1), many (*), zero or more (0..*), one or more (1..*), or a specific number (n). In this example, a time interval can be associated with many (*) time instants, while a time instant can be associated with zero or many (0..*) time intervals. A time event list can be associated with one or many (1..*) time intervals while a time interval can be associated with zero or many (0..*) time event lists. Similarly, a time event list can be associated with one or many (1..*) time instants while a time instant can be associated with zero or many (0..*) time event lists.

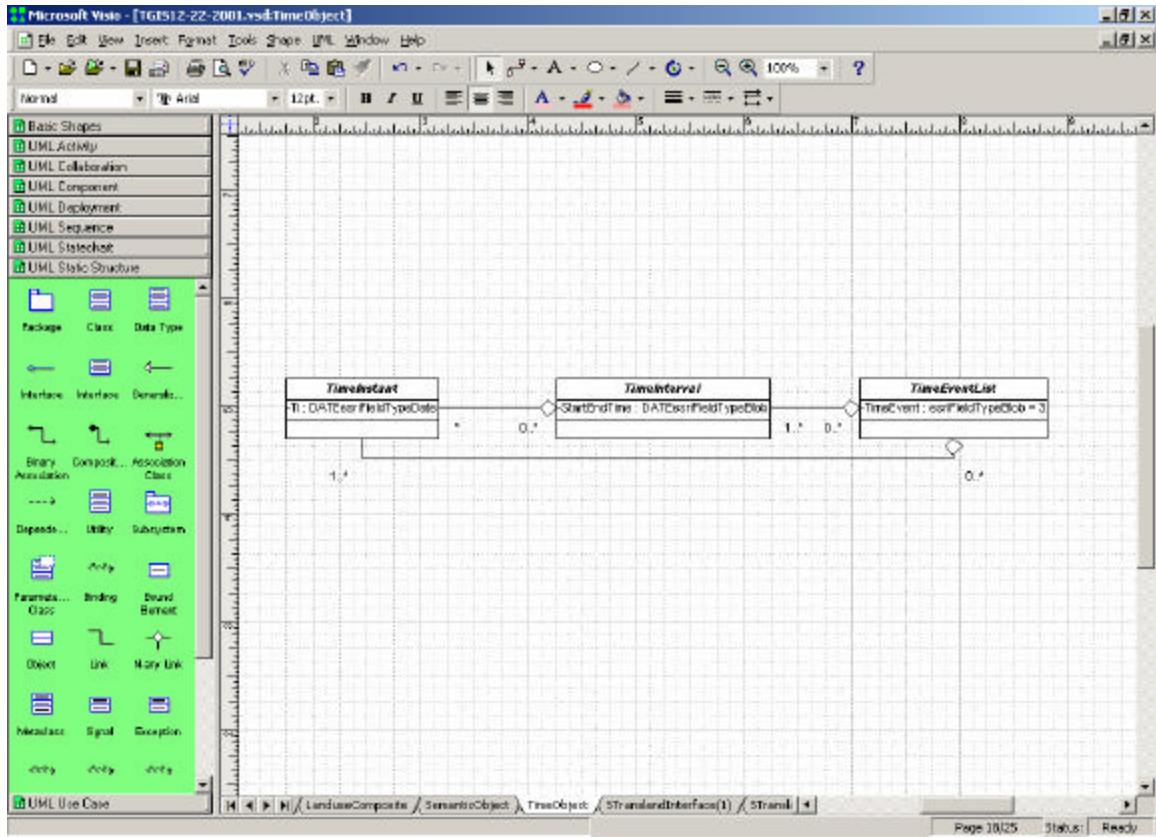


Figure 4.2: An UML Example for Class Relationships

The classes can be accessed through interfaces with custom programming, which will be discussed in the next section. A single class may expose one or multiple interfaces. An interface is a collection of related properties and methods and is separated from the implementation of the classes. In a traditional object-oriented environment, there is a one-to-one correspondence between the way you interact with the class and the implementation of the class. With ArcObjects as a COM development platform, these two parts are separated. Therefore, a class can provide multiple interfaces to manipulate the class (Figure 4.3). The UML refinement notation is used to express the relationships between a class and its interfaces.

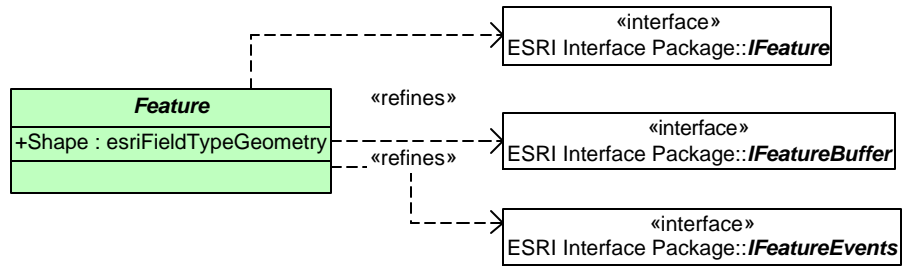


Figure 4.3: A Feature Class and its Interfaces

4.1.2 Custom Programming with ArcObjects

ArcObjects is the development platform of the ArcGIS 8 products that include ArcInfo, ArcEditor and ArcView. Since ArcObjects is built on the Microsoft Component Object Model (COM) technology, it is possible to extend ArcObjects using any COM-compliant development languages (Zeiler, 1999 and 2001). COM is a client/server architecture in which the server (or object) provides some functionality that a client can use. COM defines a protocol that connects one software component with another in a client/server environment. COM also defines an interface-based programming model that encapsulates the data and methods with each instantiated object behind a well-defined interface. ArcGIS installation includes a set of ArcObjects object model diagrams that use the UML notations to define the ArcObjects classes (with their properties and methods), interfaces available for each class, and the relationships among the classes. With this architecture, it is feasible for users to extend any part of the ArcObjects architecture.

In order to develop a number of query and analysis functions in ArcGIS 8 to support the spatio-temporal study of transportation and land use interaction, the dissertation uses the geodatabase data model and a COM-compliant programming language to develop custom tools. The interface-based programming model of ArcObjects means that all communications between objects are made via their interfaces. An interface determines what requests can be made of an object that has an implementation of the interface. Two ArcObjects classes can have the same interface, but their implementations of the interface may be different. This is known as the polymorphism of the object-oriented concepts. To develop custom database management and query and analysis tools that support a spatio-temporal GIS, the dissertation uses Visual Basic (VB) with the ArcObjects to create function-specific Dynamic Link Libraries (DLL) that will supplement the existing functions in ArcGIS 8 to handle the temporal data.

4.2 Class Packages of the Transland Spatio-Temporal Data Model

The Transland spatio-temporal data model is designed as an extension of the ESRI ArcGIS data model and is subdivided into four logical groups of related objects. Each group, or “package”, holds related or complementary sets of object classes of the overall data model. A package of object classes is related through their functions. The four main packages of the Transland spatio-temporal data model include:

- ESRI Class Package
- ESRI Interface Package

- Transland Class Package
- Transland Custom Tool Package

The ESRI Class Package and the ESRI Interface Package come with the ArcObjects installation and serve as the foundation of developing other application-specific packages. The ESRI Interface Package includes a set of pre-defined ESRI interfaces. The Transland Class Package and the Transland Custom Tools Package are designed to provide the object classes and application tools for Transland applications. Note here that COM interfaces are different from the common use of the word of interface in the context of user interfaces.

First, a workspace package is created with UML to show the logical organization of the four main packages for the Transland spatio-temporal data model (see the top part of Figure 4.4). Since many different object classes are required to support the functions of the Transland spatio-temporal data model, the Transland Class package is further divided into sub-packages in order to provide a better organization of the database design. These sub-packages are listed in the bottom part of Figure 4.4. The *Interaction package* illustrates the interaction between semantic, time and snapshot data sets. The *Transland Snapshot Dataset package* is designed to manage the snapshot data sets. This package is further subdivided into two sub-packages of Land Use and Transportation, which are not shown in the figure. This subdivision is based on the needs of analyzing the interaction between land use and transportation. The *STComposite package* is designed to combine the snapshot data sets into STcomposite GIS layers. Again, two sub-packages are created

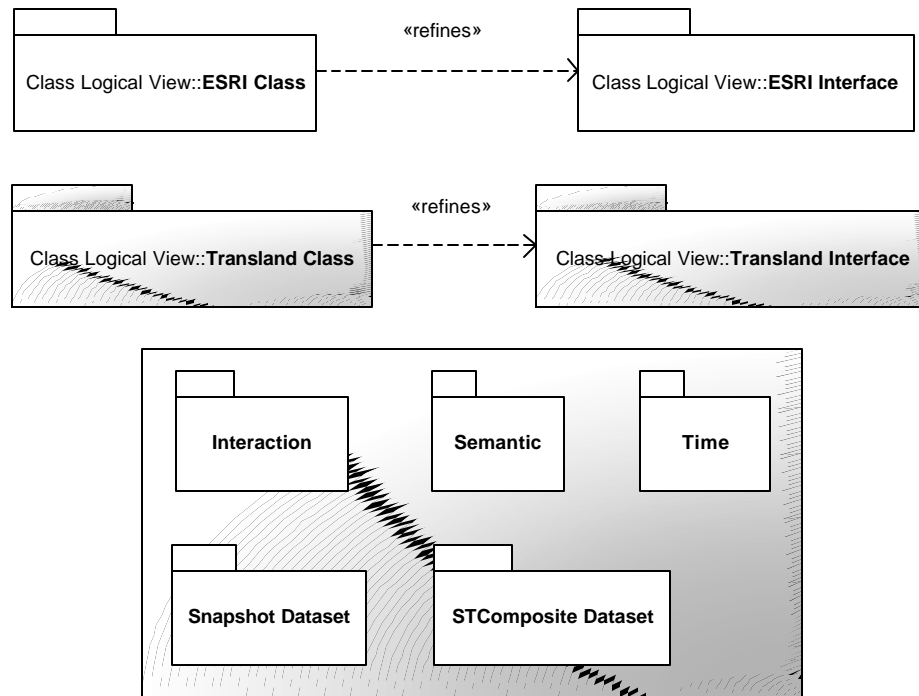


Figure 4.4: An Overview of Transland Packages

to handle the LanduseComposite and the TransportComposite respectively. The *Semantic package* is used to store semantic classes such as transportation improvement projects or land development projects. The *Time package* handles the temporal data related to various data sets. More detailed discussions of these packages and the relationships among object classes are provided below.

4.2.1 ESRI Class Package

Figure I.1 in Appendix I presents the ESRI object classes and their relationships. The top-level object class in the ESRI Class Package is the *Row Class* (see the simplified UML diagram in Figure 4.5). *Row* is a basic concept in the relational data model. The

ESRI class package is built upon the row concept since its implementation is based on a relational database management system. However, it also extends the relational data model to manage object and feature classes. An *Object Class* is a table that consists of rows representing the entities (Zeiler, 2001). A *Feature Class* is an Object Class whose objects are spatial features with geometry. The geometry is stored under a “shape” data field defined as the `esriFieldTypeGeometry` in a relational table. In ArcGIS, the geometry types include Point, Multipoint, Polyline and Polygon. The ability to store geometry in a relational database is one characteristic of the ArcGIS geodatabase data model that moves it from a relational data model into an object-relational data model. The *Object* and *Feature Classes* are critical to the creation of custom features in this dissertation. All custom classes in the Transland spatio-temporal data model are created from these two ESRI classes.

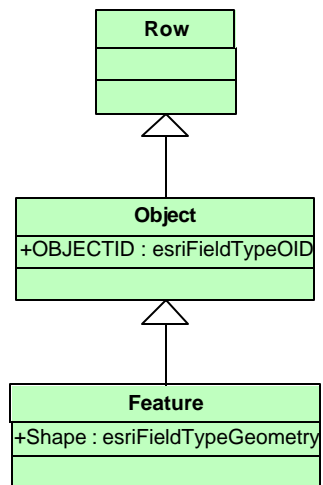


Figure 4.5: ESRI Rows, Objects, and Feature Classes

4.2.2 ESRI Interface Package

Interfaces define the behavior of classes. By convention, interface names start with the letter *I*. For example, *IRow*, *IObject*, and *IFeature* are interfaces for the *Row* class, the *Object Class*, and the *Feature Class*, respectively (Figure I.2 in Appendix I). All COM interfaces derive from the *IUnknown* interface, and all COM objects must implement this interface (Zeiler, 2001). Like the ESRI object classes, an ESRI interface can inherit from another ESRI interface. For example, Figure 4.6 shows that the *IRowEdit* interface inherits from the *IUnknown* interface. The *IFeatureEdit* interface in turn inherits from the *IRowEdit* interface. Figure 4.6 also shows a standard UML notation that includes three sections in each box of which the top section indicates the name (e.g., *IUnknown*), the middle section indicates the properties (e.g., *SubtypeCode* is a property of the *IRowSubtypes* interface class), and the bottom section indicates the methods available through an interface (e.g., *get_Fields*, *get_Value* and *put_Value* are the methods available through the *IRowBuffer* interface to read the data fields, to read the data values, and to write the data values, respectively.)

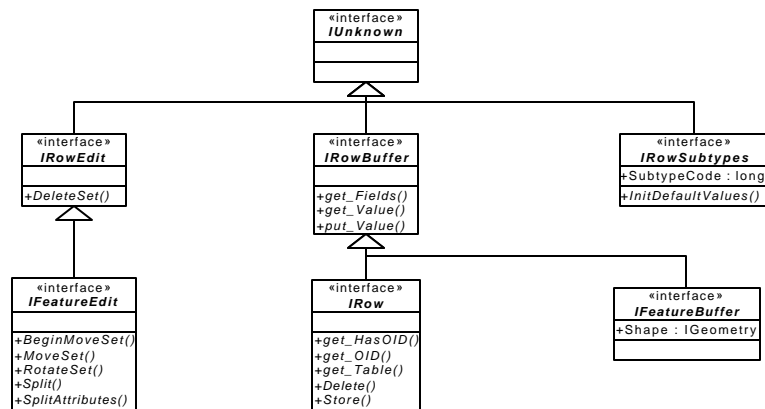


Figure 4.6: An ESRI Interface Example

4.2.3 Transland Class Package

The Transland Class package is designed to support temporal GIS needs arising from the six scenarios discussed in Chapter 3. The class package is composed of five sub-packages, which include:

- Interaction package
- Snapshot Dataset package
- STComposite package
- Time package
- Semantic package

Descriptions of each of these sub-packages are provided in the sub-sections below.

4.2.3.1 Transland Interaction Package

This package illustrates the logical view of the interaction between semantic, time, and snapshot classes to support the six scenarios. It consists of seven object classes, which are:

- Snapshot Dataset::Transportation
- Snapshot Dataset::Land Use
- STComposite Dataset::Transportation
- STComposite Dataset::Land Use

- Time::Valid Time
- Semantic::TIP
- Semantic::Land Development

These object classes organize data into Snapshot, STComposite, Time, and Semantic domains. In order to support the six scenarios to analyze the Transland interaction, the design further divides the Snapshot, STComposite, and Semantic object classes into land use and transportation categories. Details are explained below on how each scenario interacts with these domains in the Transland spatio-temporal data model. Figure 4.7 shows the flows of scenario 1 and scenario 2 in the Interaction package. Scenario 1 starts from choosing a transportation semantic object such as a transportation improvement project (Semantic::TIP) or a user-defined area. It then finds the space-attribute data (Snapshot Dataset::Transportation) related to the chosen transportation semantic object. Based on the user-specified spatial extent and land use change characteristics (i.e., the controlled component described under scenario 1 in Section 2), the system then identifies the land use feature/attribute changes (Snapshot Dataset::Land Use and STComposite Dataset::Land Use). Finally, scenario 1 will report the time objects that are related to the identified land use changes (Time::Valid Time). Scenario 2 also starts from choosing a transportation semantic object (Semantic::TIP). Instead of going directly into the interaction between transport feature/attribute changes (Snapshot Dataset::Transportation) and land use feature/attribute changes (Snapshot Dataset::Land Use and STComposite Dataset::Land Use), scenario 2 uses the user-specified time frame (Time::Valid Time) to identify the land use feature/attribute changes with respect to the

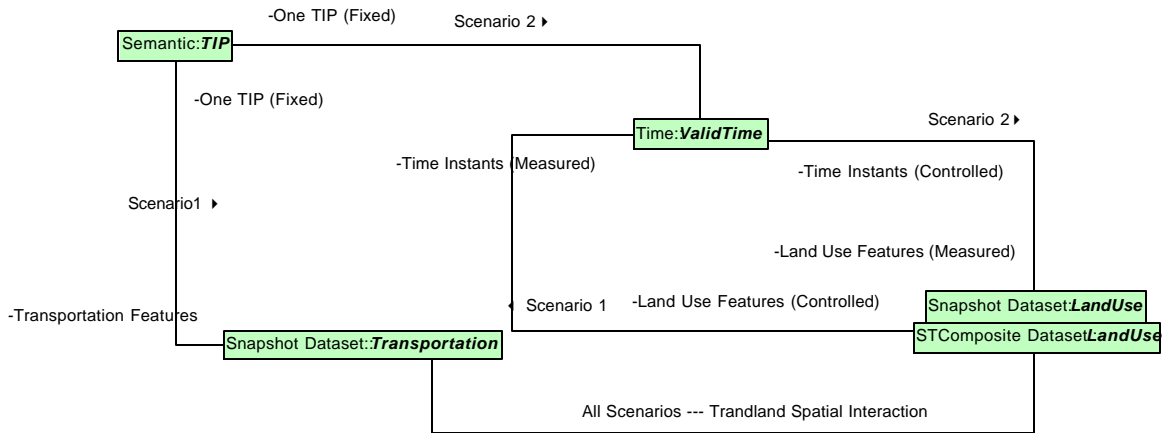


Figure 4.7: A Logical View for Scenario 1 and Scenario 2

transportation feature/attribute changes. In other words, scenario 1 identifies when the user-specified land use changes took place, while scenario 2 reports where and what land use changes took place during a user-specified time period.

Figure 4.8 shows a logical view of scenario 3 and scenario 4. Both scenarios start from choosing a time instant (Time::Valid Time). The system will automatically compute the spatial relationships between land use space-attribute data (Snapshot Dataset::Land Use) and transport space-attribute data (Snapshot Dataset::Transportation). The main difference between scenario 3 and scenario 4 is whether the user specifies the transport data or the land use data as the controlled component in order to measure the other phenomenon (i.e., land use pattern or transportation pattern). Therefore, both scenarios start from the Time::Valid Time class. Scenario 3 goes through the transportation semantic class (Semantic::TIP) and the transportation space-attribute data

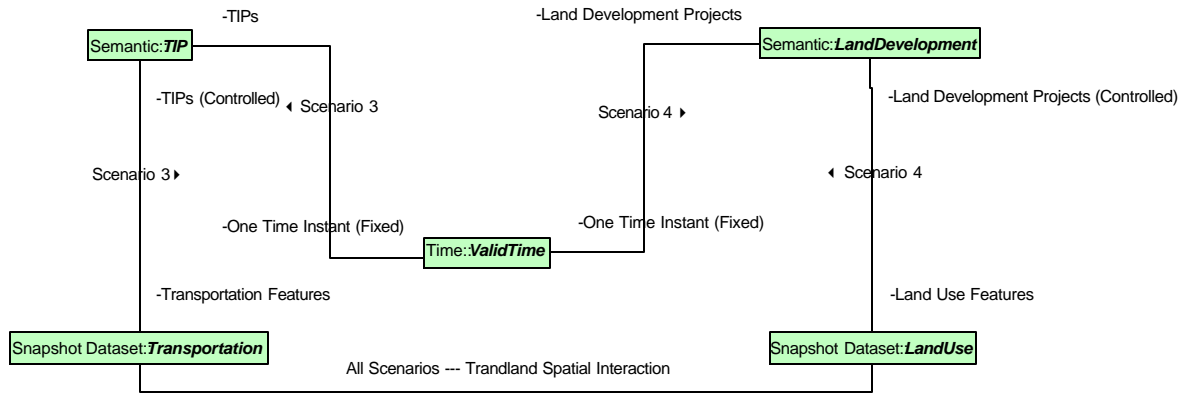


Figure 4.8: A Logical View for Scenario 3 and Scenario 4

(Snapshot Dataset::Transportation) to identify the time-specific land use changes. On the other hand, Scenario 4 goes through the land use semantic class (Semantic::Land Development) and land use feature/attribute data (Snapshot Dataset::Land Use) to identify the time-specific transportation changes.

A logical view of scenario 5 and scenario 6 is presented in Figure 4.9. These two scenarios are similar to scenarios 1 and 2, except that the land use data is used as the fixed component for scenarios 5 and 6. As a result, Figure 4.9, which starts from the land use semantic class (Semantic::Land Development), is similar to Figure 4.7 that starts from the transport semantic class (Semantic::TIP).

Note that the above logical views of the six scenarios present the abstract classes only. An abstract class is a specification for instances of subclasses through type inheritance and cannot be used to create new objects (Zeiler, 2001).

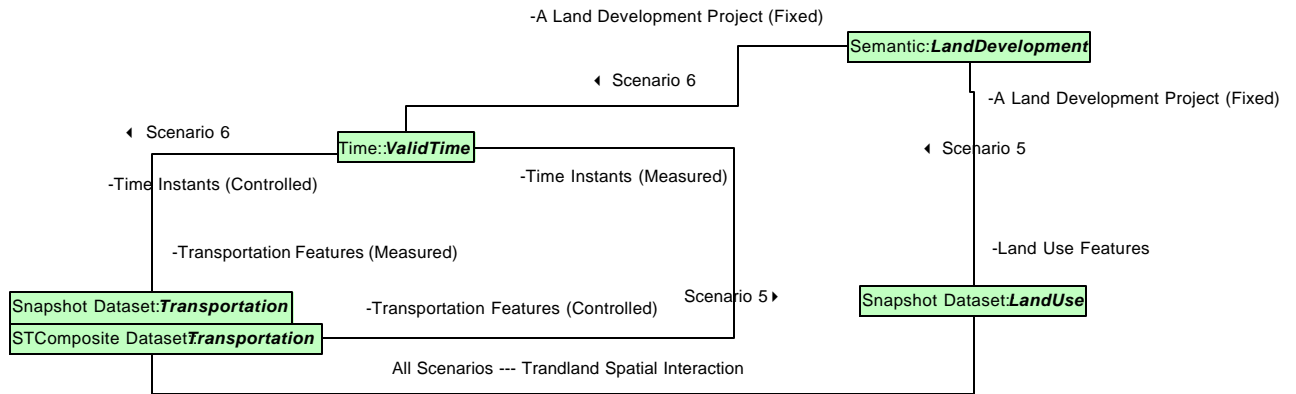


Figure 4.9: A Logical View for Scenario 5 and Scenario 6

Therefore, we must define co-classes and/or classes to make the logical design operational. In ArcObjects, a co-class can directly create new object instances through declaration statements. A class, on the other hand, cannot directly create objects. Instead, objects of a class are created as a property of another class or instantiated by objects from another class (Zeiler, 2001). The other four sub-packages (i.e., Dataset, STComposite, Semantic, and Time) included in the Transland Class Package are used to define specific co-classes and classes.

4.2.3.2 Snapshot Dataset Package

The Snapshot Dataset package is created to hold all source data sets collected for this dissertation. It is subdivided into the Snapshot Transportation Dataset package and the Snapshot Land Use Dataset package. Figure 4.10 details the Snapshot Transportation Dataset package that covers point data sets (e.g., traffic count stations), line data sets

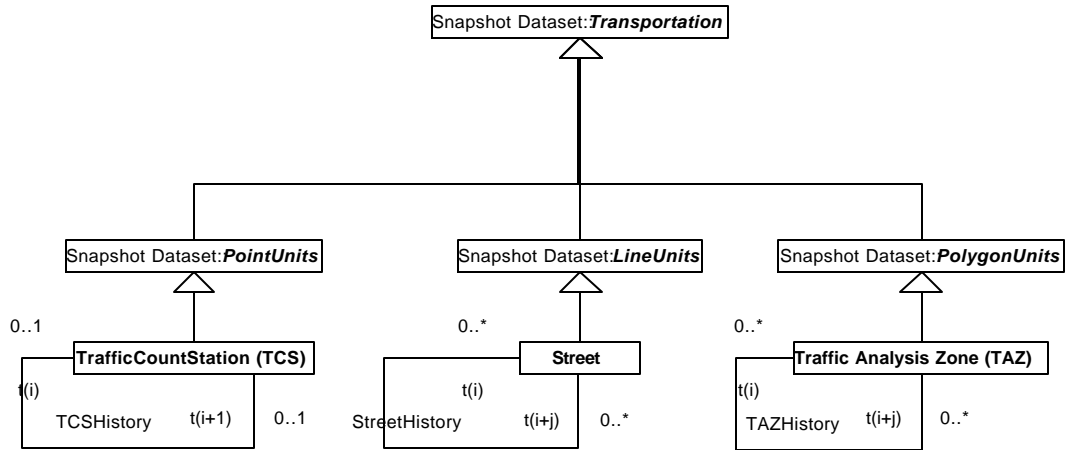


Figure 4.10: A Package for Snapshot Transportation Data Sets

(e.g., street networks), and polygon data sets (e.g., TAZs). These data sets can be ESRI coverages or shape files converted into a geodatabase.

Given the data sets collected for this dissertation, street networks, traffic count stations, TAZs, and land use boundaries have year-based feature data available. The traffic count stations are included in a single data set with the average annual daily traffic (AADT) data of different years stored under a series of attribute data fields. On the other hand, TAZ and land use data sets are stored by years. The association notation with a loop from $t(i)$ to $t(i+1)$ in Figure 4.10 is designed to handle these temporal data sets. Their specific implementations will be handled in the STComposite package discussed below.

4.2.3.3 STComposite Package

The sample data sets collected for this dissertation indicate that the time-related data are stored in different manners. One major challenge of this dissertation is to develop a spatio-temporal GIS database design that can handle and integrate these data sets in spatial, temporal and attribute domains. The space-time composite data model (STComposite) is an approach of combining snapshot GIS data sets into a composite data layer that minimizes spatial data redundancy while keeping track of the temporal changes associated with individual spatial elements.

Three STComposite classes (i.e., PointSTComposite, LineSTComposite and PolygonSTComposite) are defined to handle points, lines and polygons, respectively (Figure 4.11). Creation of these STComposite GIS layers is based on the existing spatial relationships (via the ESRI IRelationalOperator interface) and topological operators (via the ESRI ITopologicalOperator interface) available in ArcObjects (Zeiler, 1999).

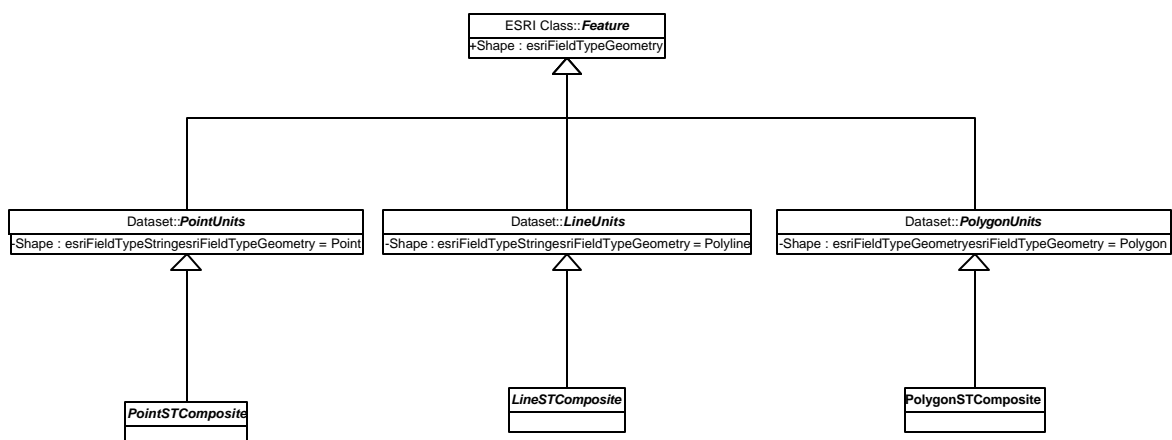


Figure 4.11: STComposite Package

It is important to note that the STComposite GIS layers will serve as the starting point rather than the ending point of this spatio-temporal GIS database design. Although the STComposite data model is a feasible way of organizing spatio-temporal GIS data, it has several limitations. First of all, the STComposite data model uses a set of data fields to keep track of changes over time. Since different entities may experience changes at different time instants, a new data field must be created for each time instant. This leads to an inefficient database design because of the redundant values stored in the cells of those records with no changes. Secondly, the storage of time-related data under different data fields requires a structured query language (SQL) to check many data fields in order to retrieve the relevant data based on a user-specified time period. This approach leads to a poor system performance when we deal with a large database. In addition, the temporal information is implicitly stored with the data field names under this approach. For example, we would need to create data fields such as Landuse1990, Landuse1991, Landuse1992, etc. in order to store the land use data associated with each record for different years. This implicit representation of temporal information prevents users from direct access to temporal data. A more explicit way of storing temporal data is to add time stamps as data values in a database. The Transland spatio-temporal data model will first generate STComposite GIS layers from the snapshot GIS layers and then implement the Time object classes to re-organize the STComposite data according to the concepts of three-domain data model. Additional discussions of these custom tools are provided in Section 4.2.4 below.

4.2.3.4 Time Package

Commercial GIS products have developed efficient ways of integrating spatial and attribute data for various spatial analysis needs. The approach in the dissertation is to take full advantage of the existing GIS software capabilities while extending them into the temporal domain. In the Transland spatio-temporal data model, time object classes are created to store temporal data explicitly. These time objects, in turn, are associated with their corresponding feature/attribute data derived from the spatio-temporal composite layers. This design approach makes it feasible to access the spatial, temporal, and attribute data individually as well as to easily access their associated data in other domains. For example, users could first use the existing GIS functions to select features of interest based on locations and/or attributes. Once these features are identified, their associated temporal data can be easily retrieved for spatio-temporal analysis. Users also could use the time objects defined in the Transland spatio-temporal data model to quickly find the features of interest at a given time instant or during a specific time interval. Existing GIS functions then could be used to display these features or to perform additional analysis of these features. Associations between the time objects and their corresponding features are maintained through the unique IDs generated in the spatio-temporal composite layers. The same time object can be associated with different types of features (e.g., traffic count stations, TAZs, street segments, property parcels). This allows users to access all relevant data from the time objects. As a result, it is possible to examine the interaction between different data sets through the time domain.

A spatio-temporal GIS database should include both valid time (i.e., when an event actually occurs in the real world) and transaction time (i.e., when a transaction takes place in the database). Both of them are included in the Time package (Figure 4.12). The sample data sets collected for the project so far, however, indicate that transaction time is not recorded in the data sets. Consequently, the dissertation focuses on the valid time. A transaction time class could be further developed in the future. There are three possible valid time object classes. The TimeInstant class is for single time points. The TimeInterval class is defined by a start time instant and an end time instant. The TimeEventList class can consist of multiple time instants and/or multiple time intervals (the latter is not implemented in the dissertation). The empty-diamond notations in Figure 4.12 indicate that the TimeInterval class is an aggregation of time instants and the TimeEventList class is an aggregation of time instants and/or time intervals. With this design, time is modeled as explicit classes rather than hidden information implied in the data field names in a relational table.

4.2.3.5 Semantic Package

The Semantic package is designed to deal with application-specific entities that do not fit well with the conventional GIS layer concept. For example, a transportation improvement project (TIP) or a land use development is best represented as an object by itself that is associated with different spatial and attribute data over time (i.e., *TIP object class* and *LandDevelopment object class*). Transportation planners often need to retrieve

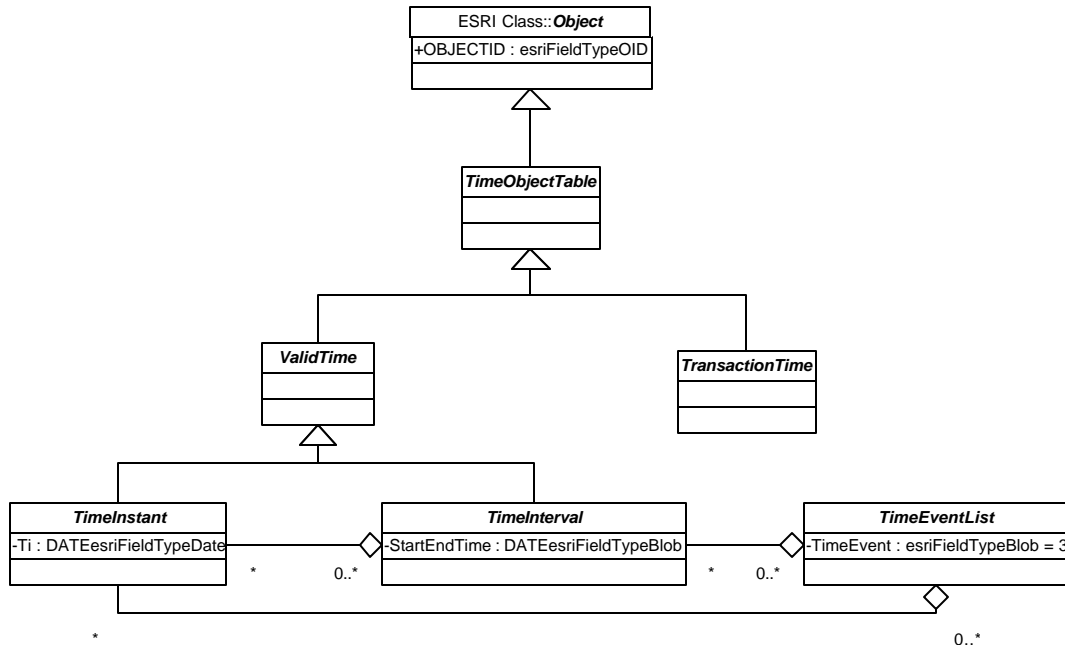


Figure 4.12: Time Package

the temporal, spatial and attribute information related to a TIP or a land use development. The most intuitive way of performing such tasks is to access them through the project names or the project IDs. Semantic object classes defined in the Transland spatio-temporal data model will facilitate these tasks. There are two initial types of semantic classes included in the Transland spatio-temporal data model, which are Transportation and Land Development (Figure 4.13). They inherit from the ESRI Object Class. It is also anticipated that they will have associations with the ESRI Feature Classes of TIP through “PRJ_ID” and LandDevelopment through “FOLIO”.

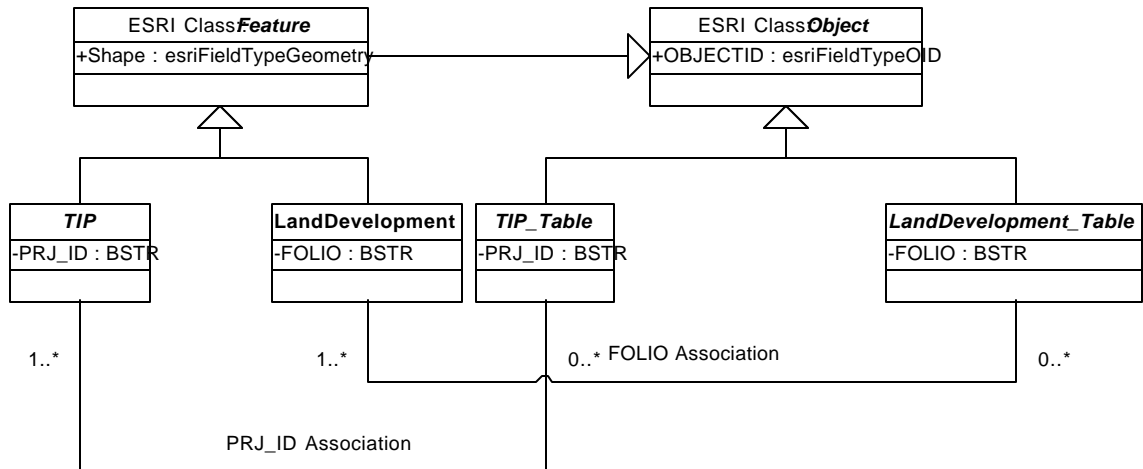


Figure 4.13: Semantic Package

4.2.4 Transland Custom Tools

As mentioned previously, COM is an interface-based programming model that encapsulates the data and methods with each instantiated object behind a well-defined interface. The ESRI ArcGIS data model provides a rich set of interfaces for programmers to access and manipulate various ArcObjects classes in different modules. For this dissertation, the most relevant modules are *ArcCatalog*, *ArcMap*, *Geodatabase*, and *Geometry*. The Transland physical data model uses *ArcMap* to implement graphic user interfaces (GUI) for data management, access, analysis and display functions. The *Geodatabase* module serves as the data model of organizing various data sets into a geodatabase, which will be implemented as a personal geodatabase using the Microsoft Access database format. The *Geometry* module handles the geometry of features that are stored in feature classes or as other graphical layers.

Most custom tools that are developed for this dissertation are based on the ArcObjects interfaces. The ESRI Interface Package discussed in Section 4.2.2 only shows a very small set of ArcObjects interfaces used in the ArcGIS transportation data model. In order to illustrate additional ArcObjects interfaces for this dissertation, Figure I.3 in Appendix I presents an Extended ESRI Interface package. Those interfaces that are not included in the original ESRI Interface package are highlighted with a gray background color.

The *IFeatureWorkspace* interface includes a set of methods to manage (e.g., list, add, delete, copy or rename) a collection of feature data sets. A feature workspace may be implemented as a directory in the file system (for ArcInfo coverages and ArcView shapefiles) or as a relational database (for geodatabases). Users must open a workspace before accessing data sets in that workspace. For example, the *OpenFeatureDataset* method of *IFeatureWorkspace* interface is used to open an existing feature data set in the workspace. *IDataset* inherits from the *IFeatureWorkspace*. A *Dataset* is an abstract class that represents both geographic and non-geographic data collections such as tables, feature classes, grids and images. *IFeatureDataset* and *ITable* in turn inherit from the *IDataset*. An *IFeatureDataset* is an *IDataset* that consists of one or more *IFeatureClasses*. Its associated interface, *IFeatureLayer*, handles the common aspects of visual presentation of the underlying data in ArcMap. The *ITable* interface provides access to members that manage and return information about tables. The *IFields* interface, which is associated with the *ITable* interface, allows users to access individual data fields.

Several types of custom tools are needed to manage and create the snapshot data sets, the STComposite layers, the semantic objects and the time objects under the geodatabase data model. First of all, source data sets for this dissertation may be available in ArcInfo coverage, ArcView shapefile, dBase or text file formats. It is also likely that the same feature type (e.g., TAZs) of different years may include different data fields and/or different data field names. Custom tools must be developed to consolidate these source data sets and convert them into a geodatabase stored in the Microsoft Access format. Secondly, source data sets will include points, lines and polygons. In order to create STComposite GIS layers from these different geometry types, we will need custom tools to derive the spatial, attribute and temporal changes of point data, line data and polygon data. Thirdly, semantic objects such as transportation improvement projects and land development projects must be organized into semantic classes. These semantic objects in turn are associated with their corresponding spatial, temporal and attribute data stored in other tables. Finally, time is a key component of organizing these various data sets. The temporal data derived from the STComposite creation processes must be organized and stored in the Time object classes that will allow operations such as insertion and deletion.

4.3 Summary

The chapter proposes a design of the Transland spatio-temporal data model using commercial GIS software. ESRI ArcGIS and its components offer an OOA&D environment along with a collection of spatial object classes (i.e., ESRI classes) as well

as their interfaces (i.e., ESRI interfaces) for designing the Transland classes and the spatio-temporal object classes. Categorized into packages (a term for grouping classes), the Transland classes consist of packages of snapshot, STComposite, time, and semantic, as well as an interaction package that interprets the Transland scenarios with the composition of the spatio-temporal object classes. This chapter describes all Transland classes and identifies their relationships. It also introduces the Transland custom tools for constructing and generating the Transland classes. Unlike ESRI interfaces, the Transland custom tools are not designed as COM interface-based, but as a set of Visual Basic functions for exploratory analysis of the Transland classes. The next chapter will present Transland personal geodatabases and Transland GUI. The Transland personal geodatabases are Access databases managing the Transland classes. The Transland GUIs include a set of controls in correspondence with the Transland custom tools designed in this chapter.

5 THE IMPLEMENTATION OF THE TRANSLAND SPATIO-TEMPORAL DATA MODEL

The previous chapter presented the design of the Transland spatio-temporal data model by identifying land use and transportation data sets as well as their relationships in association with the components of the Transland scenarios. For instance, snapshot and STComposite street data sets could be used for the transportation component and snapshot and STComposite CENSUS tract data sets for the land use component. They all include a time component. The design provides guidance for implementing the Transland spatio-temporal data model, which is the focus of this chapter. The first section in this chapter describes various Transland classes included in the system design of the Transland spatio-temporal data model. The second section discusses the implementation of user interfaces that integrate the Transland classes and analysis tools for transportation planners to explore spatiotemporal interactions of land use and transportation systems under the various scenarios.

5.1 Implementing the Transland Classes

Mirroring the Transland class packages discussed in the previous chapter, the Transland classes are grouped into four types -- snapshot component, STComposite component, time component, and semantic component. Class and sequence diagrams are used to show static and dynamic relationships of the Transland classes, respectively.

Figure 5.1 is a unified modeling language (UML) class diagram consisting of the four components and their associated Transland classes. Each Transland class has a parent class of either an ESRI feature class or an ESRI object class. The feature classes are white boxes representing GIS layers with spatial references, while the object classes are gray boxes containing attribute information. The "snapshot component" block in Figure 5.1 stores and manages the snapshot GIS data sets collected by the FIU team using the built-in functions available in ArcGIS 8. These snapshot data sets are organized into transportation-related data sets and land use-related data sets, respectively. Time associated with these snapshot data sets is often implied in the file name or provided through a metadata document. Explicit time-stamps normally are not included in the data fields of these datasets. Therefore, the first step is to add time-stamps into the snapshot data sets (as indicated by the $t(i)$ and $t(i+j)$ loops in Figure 5.1). The "space-time (ST) composite component" block consists of a set of custom Visual Basic programs to generate space-time composite GIS databases from the snapshot GIS data sets. Each space-time composite GIS database combines all snapshot GIS layers of a particular theme (e.g., land use) into a single GIS database that consists of spatial and attribute changes over time. In addition, the custom Visual Basic programs also automatically create a Time object class to record all unique time instances associated with the snapshot GIS layers, as well as a Time2Space object class to associate the unique identifier of each geographic unit in a space-time composite database with all time instances that exist in the individual snapshot layers. The Time object class and the Time2Space object class make up the "time component" block identified in Figure 5.1.

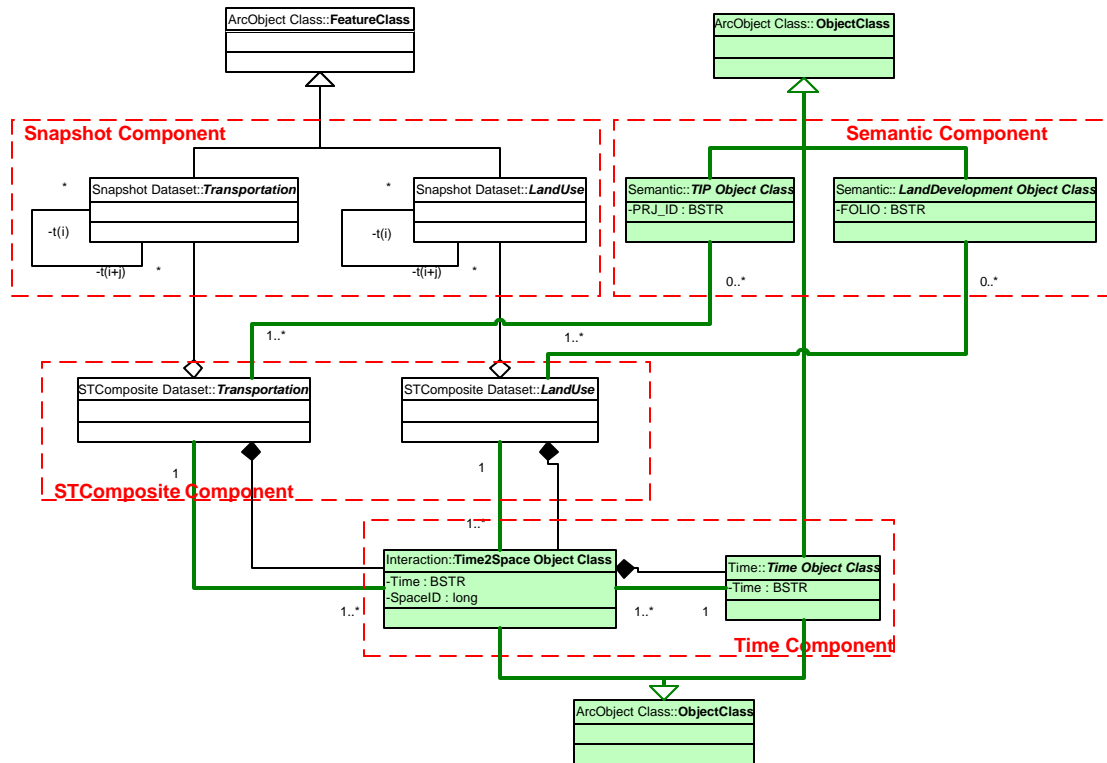


Figure 5.1: Transland Classes

The "semantic component" block is designed to handle entities that are associated with different locations and attributes at different time instances. For example, a transportation improvement project (TIP) often consists of multiple phases. Each phase may be associated with works on different highway locations and may have different attribute values (e.g., budget amount spent at each phase). To facilitate spatiotemporal analysis of processes such as transportation improvement projects and land development projects, we also define Semantic object classes that allow linkages of a single semantic object instance to multiple locations and attributes over time.

A UML sequence diagram shown in Figure 5.2 reflects dynamic associations

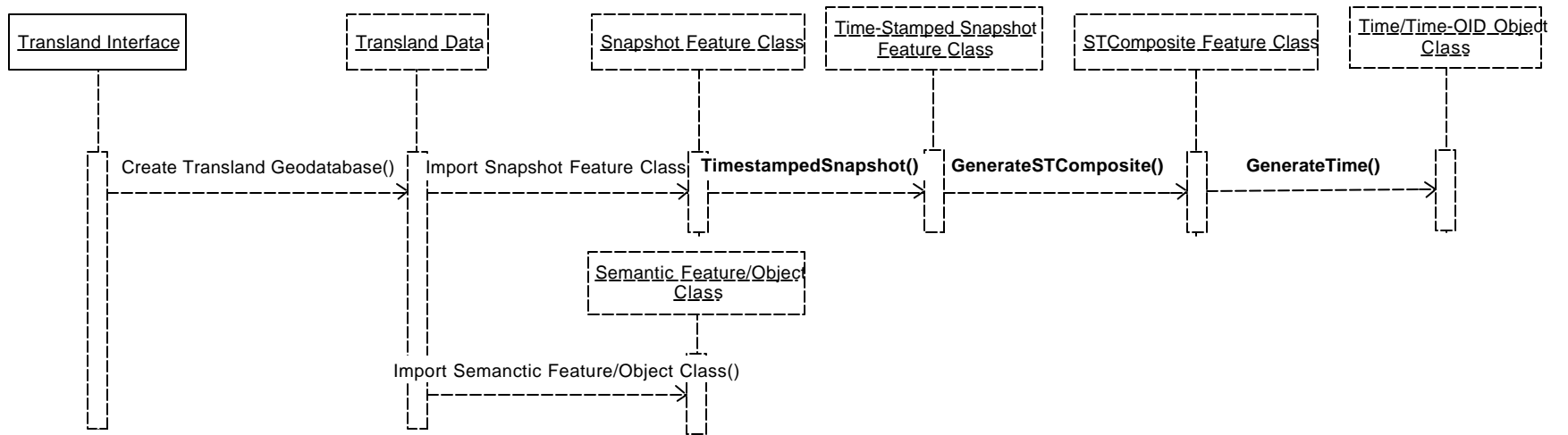


Figure 5.2: Transland Classes in a UML Sequence Diagram

among the Transland classes. The Transland classes are lined up horizontally to represent a sequence of steps used in creating each Transland class in this study. The height of vertical boxes with dotted lines linked to the Transland boxes indicates class duration. Operations between the classes are carried through one-way arrows between the vertical boxes. The diagram covers two kinds of functions. One type includes necessary steps to construct the framework of the Transland personal geodatabase and to import GIS layers of the Snapshot Feature Class and the Semantic Feature Class. The other type refers to the custom programs for generating derived Transland classes such as the STComposite Feature Class and the Time Class. For example, the Snapshot Feature Class is time-stamped through a “TimeStampedSnapshot” function to create the time-stamped Snapshot Feature Class, which is then used to generate the STComposite with the “GenerateSTComposite” function.

5.1.1 Managing the Transland Classes with the Transland Personal Geodatabases

The Transland personal geodatabases help store various time-varying feature classes and object classes in a single Access database. Well-structured Transland personal geodatabases provide advantages for snapshot data retrieval and creation of other Transland classes.

5.1.2 An Overview of the Transland Personal Geodatabase

The Transland data model is used to process land use and transportation data sets of Miami-Dade County in Florida. These data sets are in ArcView shapefiles and dBase file formats. This study develops procedures to convert the ArcView shapefiles into feature classes and the standalone dBase files into object classes. Figure 5.3 shows a summary of the data sets.

First, the study employs the following snapshot data sets that are used to generate STComposite feature classes.

- TAZ (i.e., Traffic Analysis Zone) data set includes 1992 and 2000 snapshot feature classes;
- Street (i.e., Street Network) data set includes 1996, 1997, 1999, and 2000 feature classes;
- LOS (i.e., Level of Service) data set includes 1999 feature class;
- Tract (i.e., Census Tract) data set includes 1980, 1990, and 2000 feature classes;
- LU (i.e., Land Use) data set includes 1994 and 1998 feature classes.

Second, AADT (i.e., Average Annual Daily Traffic) data set includes an STComposite feature class, along with snapshot feature classes between 1970 and 2000.

AADT could be treated the same as other STComposite feature classes.

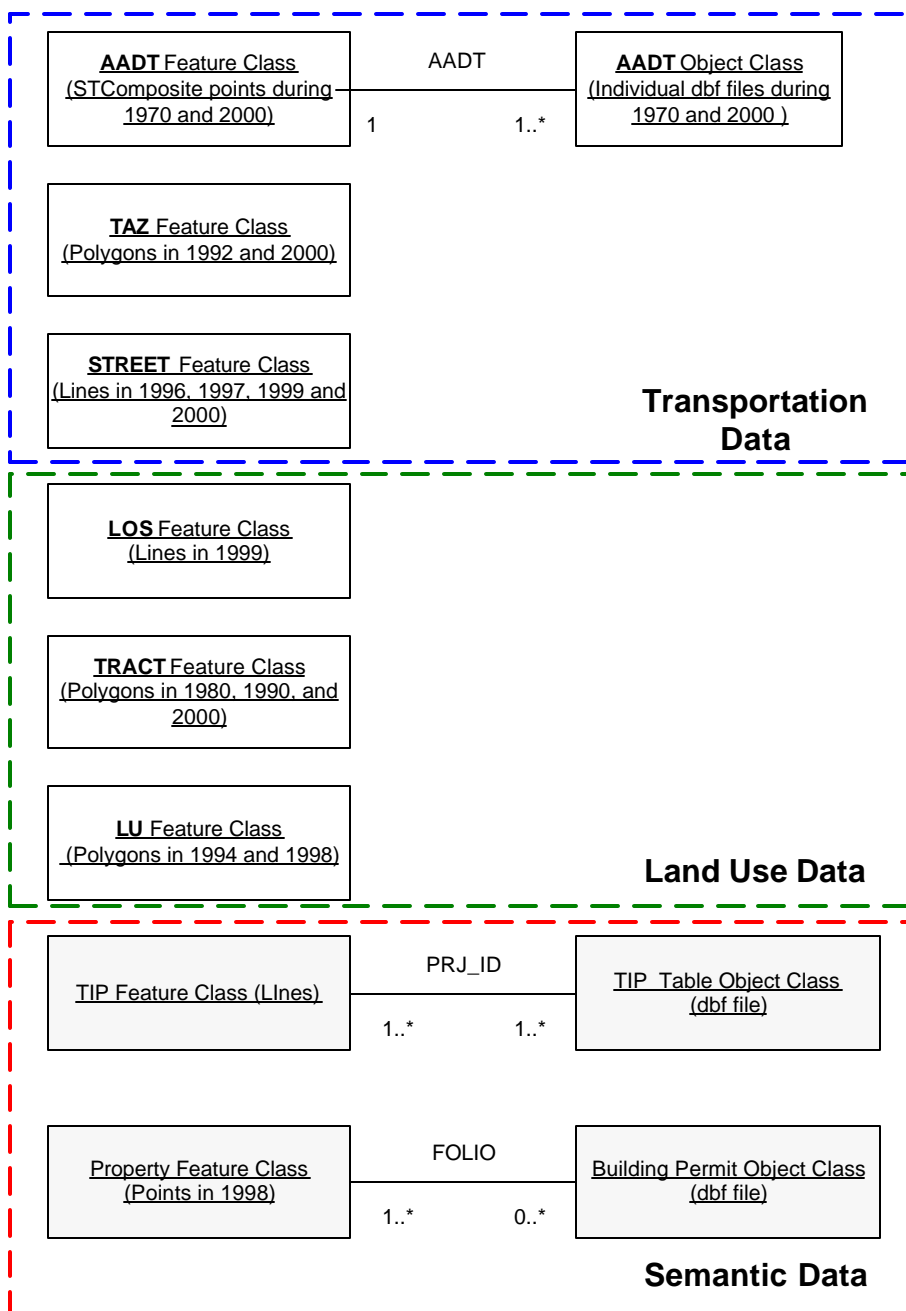


Figure 5.3: Transland Data

Third, TIP and Building Permit data sets are regarded as semantic classes. Both TIP and Building Permit semantic classes are pairs of a feature class and an object class. The feature class identifies the locations of the semantic objects while the object class stores attributes in association with the feature class relevant to the semantic objects. The original TIP data set is an attribute data file with a collection of transportation improvement projects. It is associated through a foreign key of “Project_ID” with the TIP feature class. The original Building Permit data set is another attribute data file representing land development projects. It also has a spatial counterpart, which is the 1998 Property (i.e., Land Property) feature class.

The Transland personal geodatabases, developed within the ArcGIS ArcCatalog, allow users to organize data hierarchically into different classes (e.g., feature datasets, feature classes, object classes). Within the hierarchy described in Figure 5.4, feature datasets are stored in a geodatabase, which hosts feature classes with a defined geographic reference that applies to all feature classes in a feature dataset. Object classes are attribute tables that are stored as stand-alone tables inside the feature dataset. The Transland spatio-temporal data model is implemented to have multiple geodatabases according to the types of available Transland data. Each of them has one feature dataset that stores snapshot, time-stamped snapshot, and STComposite feature classes. Since there are data sets for Streets (Street Network), TAZ (Traffic Analysis Zone), LOS (Level of Service), and AADT (Average Annual Daily Traffic), LU (Land Use) and TRACT (Census Tract), corresponding geodatabases are created for each data set. TIP



Figure 5.4: Transland Personal Geodatabases

(Transportation Improvement Project) and land development feature and object classes are stored in a semantic geodatabase. Besides the feature datasets and feature classes discussed above, there also exist time-related object classes derived from them, such as Time object classes, and Time2Space object classes. They are organized at the same level as the feature datasets in each geodatabase. An organization of these geodatabases, feature datasets, feature classes, and object classes is depicted below.

Transland Data folder

- TAZ geodatabase (taz.mdb)
 - o TAZ feature dataset
 - TAZ snapshot feature class
 - TAZ time-stamped feature class
 - TAZ STComposite feature class
 - o TAZ Time object class
 - o TAZ Time2Space object class
- LOS geodatabase (los.mdb)
 - o LOS feature dataset
 - LOS snapshot feature class
 - LOS time-stamped feature class
 - LOS STComposite feature class
 - o LOS Time object class
 - o LOS Time2Space object class
- AADT geodatabase (aadt.mdb)
 - o AADT feature dataset
 - AADT snapshot feature class
 - AADT time-stamped feature class
 - AADT STComposite feature class
 - o AADT Time object class
 - o AADT Time2Space object class
 - o AADT object class
 - o AADT relationship class
- LU geodatabase (lu.mdb)
 - o LU feature dataset
 - LU snapshot feature class
 - LU time-stamped feature class
 - LU STComposite feature class
 - o LU Time object class
 - o LU Time2Space object class
- TRACT geodatabase (tract.mdb)
 - o TRACT feature dataset

- TRACT snapshot feature class
- TRACT time-stamped feature class
- TRACT STComposite feature class
- TRACT Time object class
- TRACT Time2Space object class
- Semantic geodatabase (semantic.mdb)
 - TIP feature class
 - TIP object class
 - LandDevelopment feature class
 - LandDevelopment object class

5.2 Implementing Custom Tools on Transland Graphic User Interface (GUI)

The Transland Graphic User Interface (GUI) includes a set of custom tools for facilitating spatio-temporal exploratory data analysis. Figure 5.5 illustrates these custom tools embedded in the Transland GUI. They execute the following functions:

- Transland property tool (Figure 5.6(a)). This is a tool critical for all other functions. It is set up at the very beginning to locate the files of the Transland personal geodatabases, Microsoft IExplore.exe and Java classes. The Transland personal geodatabases are stored in Access files in one folder. The Microsoft IExplore.exe and Java classes are needed to display Transland data animation, which is shown in Figure 5.7.
- Transland animation tool (Figure 5.6(b)). This tool is independent from the other tools. Without going through procedures of time-stamping snapshot feature classes and generating their STComposite feature class, this tool allows analysts to dynamically visualize the changes of snapshot feature classes within a user-specified time frame. Its GUI allows users to define a time period, choose data sets that contain snapshot feature classes within the time period, and select a

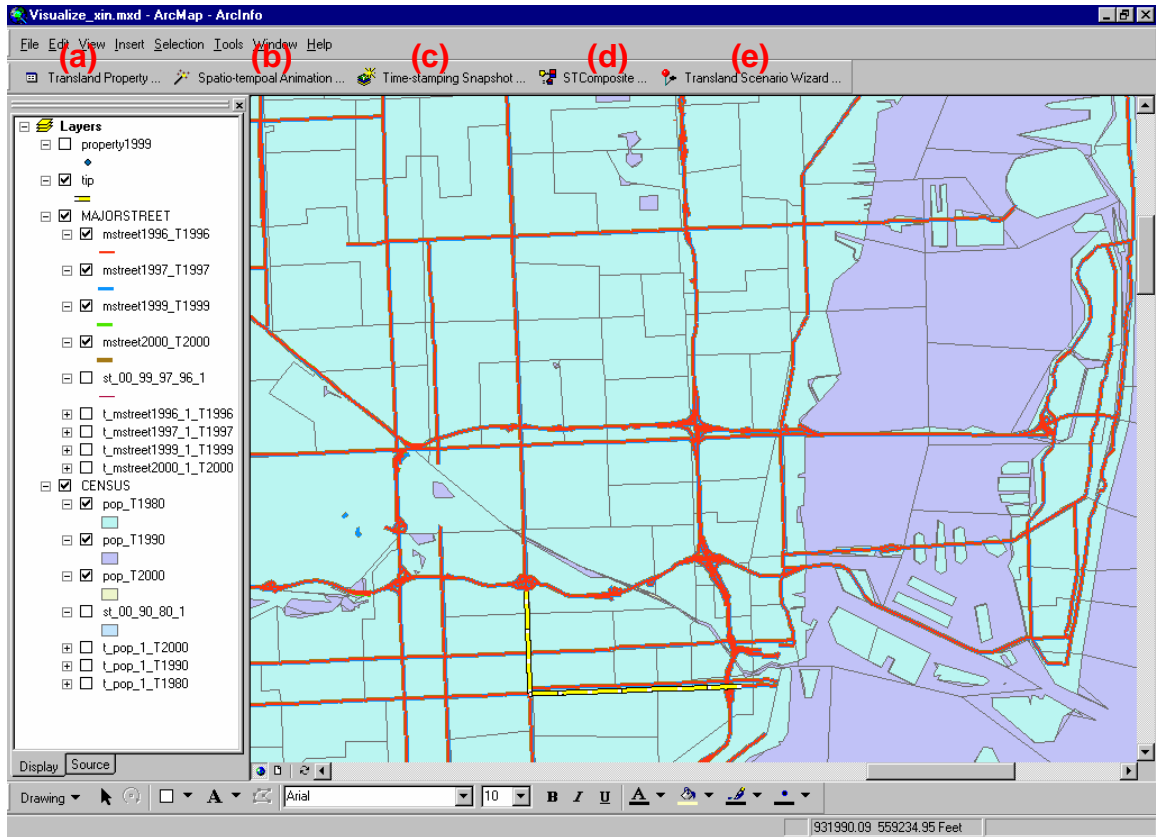
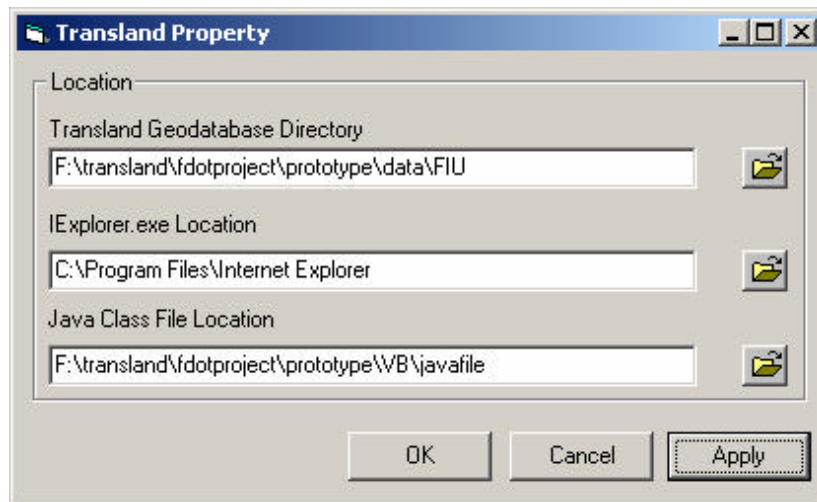
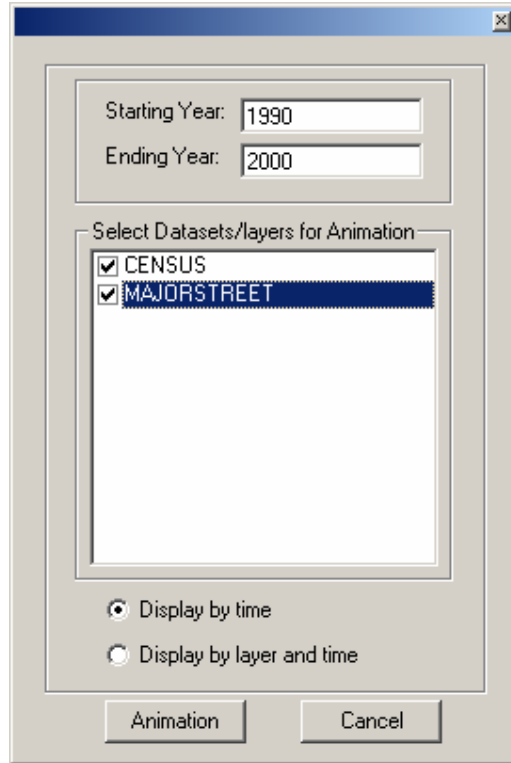


Figure 5.5: The Transland ArcMap GUI

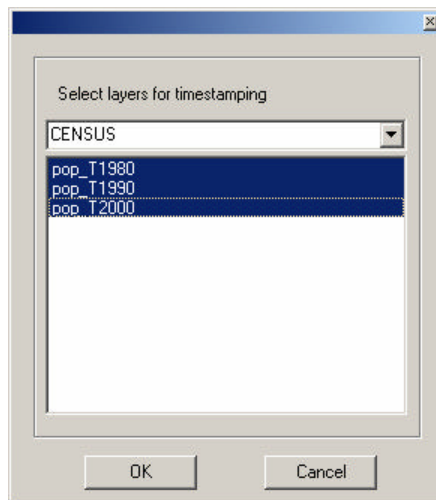


(a) Transland Property Tool Window

Figure 5.6: The Transland GUI and its Custom Tools

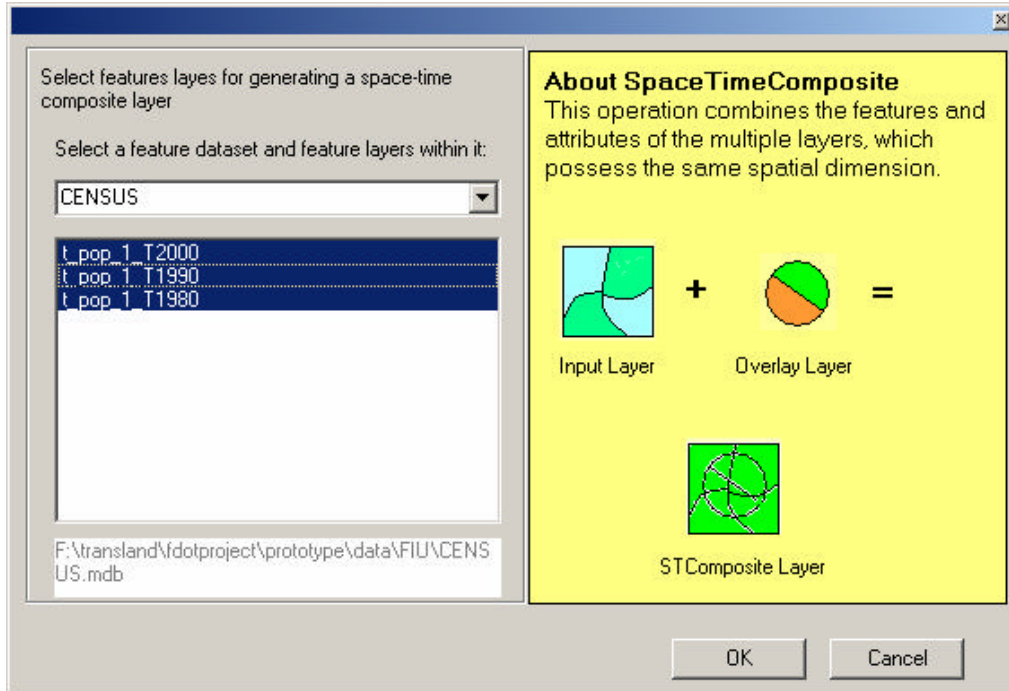


(b) Transland Animation Tool Window

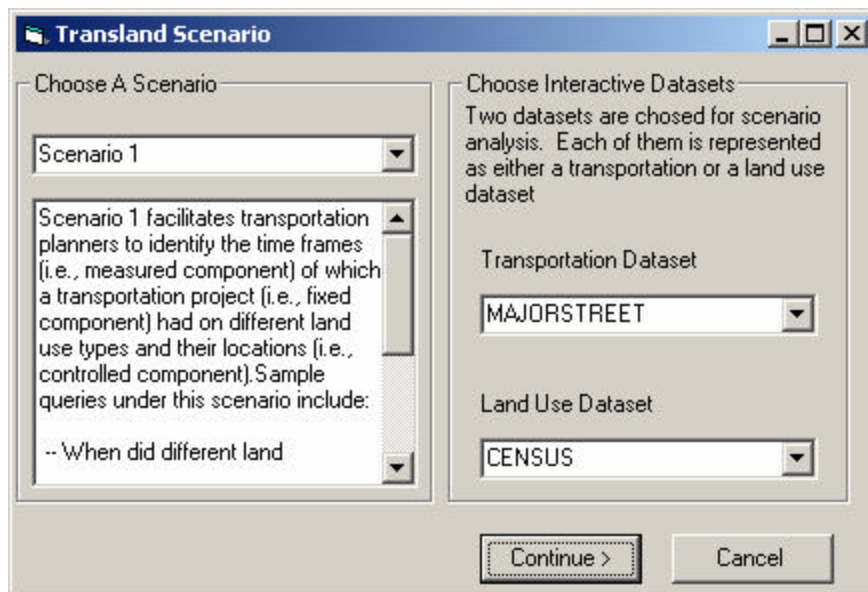


(c) Time-stamping Tool Window

Figure 5.6: Continued



(d) STComposite Generation Tool Window



(e) Transland Scenario Tool Window

Figure 5.6: Continued

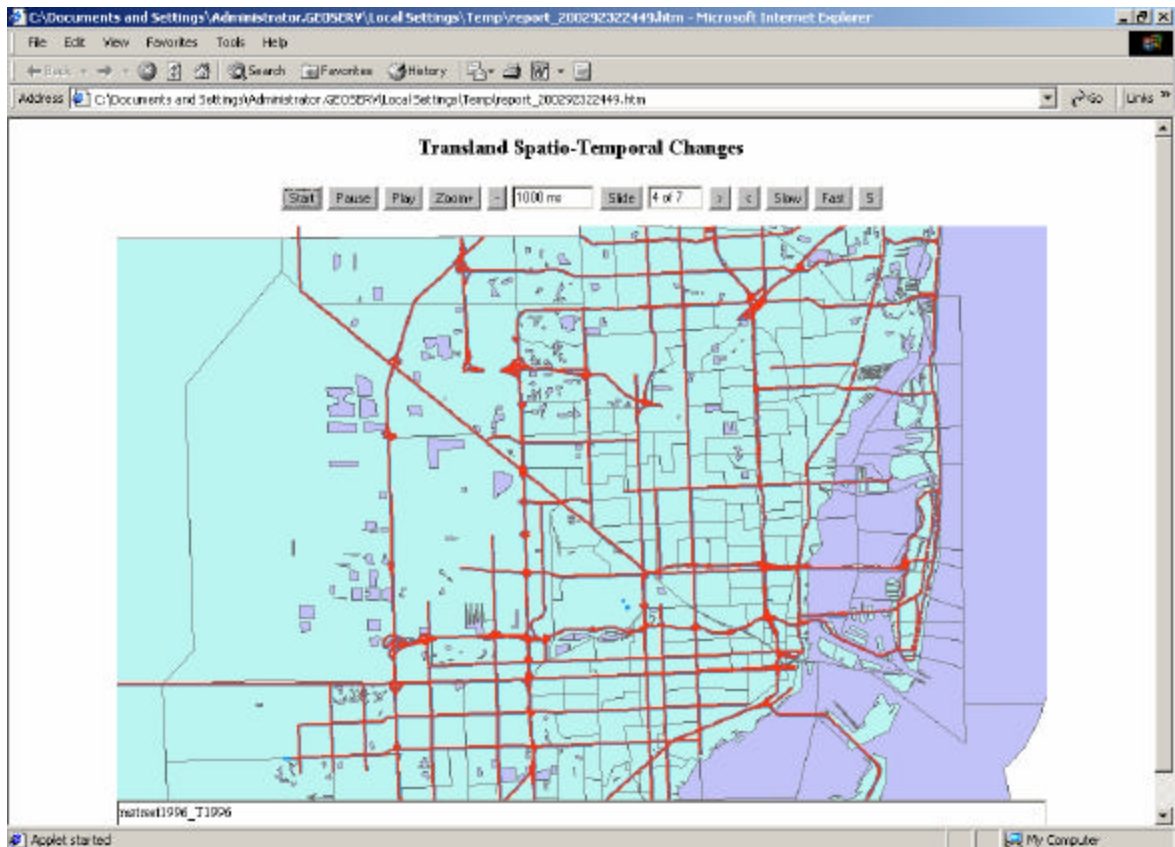


Figure 5.7: An Example from Transland Animation

method of animating the snapshot feature classes either by years (e.g., 1980 CENSUS, 1990 CENSUS, 1996 MAJORSTREET, 1997 MAJORSTREET) or by data sets and then years (e.g., 1980 CENSUS, 1990 CENSUS, 1996 MAJORSTREET, 1997 MAJORSTREET). Figure 5.7 is an output from the Transland animation. Its GUI is developed with Java containing a series of buttons at the top of the display window to control animation speed (Start, Pause, Slow, Fast, Stop, etc.) and resolution (Zoom+, Zoom-). The names of the snapshot feature classes are shown at the bottom of the display window.

- Time-stamping snapshot tool (Figure 5.6(c)). Its GUI allows users to choose what kind of snapshot feature classes are to be processed to create time-stamped snapshot feature classes.
- STComposite generation tool (Figure 5.6(d)). It chooses more than one time-stamped snapshot feature classes, then creates a STComposite feature class from the selected snapshot feature classes.
- Transland scenario tool (Figure 5.6(e)). It consists of controls to choose a specific scenario and the data sets of transportation and land use. For example, Figure 5.6(e) shows the scenario 1 with MAJORSTREET as the transportation data set and CENSUS as the land use data set.

Implementing the Transland property tool (Figure 5.6(a)) and the Transland animation tool (Figure 5.6(b)) does not involve complicated procedures. The following section will skip their discussion and only present detailed procedures on the implementation of the tools for Figure 5.6(c) through 5.6(e).

5.2.1 Time-stamping Snapshot Feature Classes

An initial step before generating an STComposite class from the snapshot feature classes is to append time to the fields in the snapshot feature classes and add a time-stamp field. This step is crucial because the snapshot feature classes of various years are likely to contain identical field names. When these fields from different snapshot data sets are combined into a single STComposite feature class, it is critical to be able to tell the time

with which each field is associated (Table 5.1). The time-stamped snapshot feature classes are stored at the same level as the snapshot feature class with its name prefixed with a “t_”.

An ArcObject VB function named “TimeStamped Snapshot” is developed to time-stamp the fields of each snapshot feature classes. Figure 5.8 presents a UML activity diagram with a logical flow of steps taken to time-stamp a snapshot feature class. The flow starts with appending every non-OBJECTID field with a time indicator (e.g., SITETYPE_T1999 in Table 5.1). Then, an empty feature class with the time-stamped field list is populated with the old feature classes.

The upper part of Figure II.1 in Appendix II lists VB class modules, standard modules, and forms, which constitute a VB project used for time-stamping snapshot feature classes. The lower part illustrates an example of ICommand, a Microsoft COM interface customized to become an ArcObjects COM so that the time-stamping function

Table 5.1: An Example of Time-stamping Snapshot Feature Classes

| OBJECTID | SITETYPE | SITE_ID |
|----------|----------|---------|
| 1 | Portable | 14 |
| 2 | Portable | 94 |
| 3 | Portable | 289 |
| 4 | Portable | 311 |
| 5 | Portable | 313 |
| 6 | Portable | 346 |
| 7 | Portable | 374 |
| 8 | Portable | 406 |

Snapshot Feature Class

| OBJECTID | SITETYPE_T1999 | SITE_ID_T1999 | T1999 |
|----------|----------------|---------------|-------|
| 1 | Portable | 14 | 1 |
| 2 | Portable | 94 | 1 |
| 3 | Portable | 289 | 1 |
| 4 | Portable | 311 | 1 |
| 5 | Portable | 313 | 1 |
| 6 | Portable | 346 | 1 |
| 7 | Portable | 374 | 1 |
| 8 | Portable | 406 | 1 |

Time-stamped Snapshot Feature Class

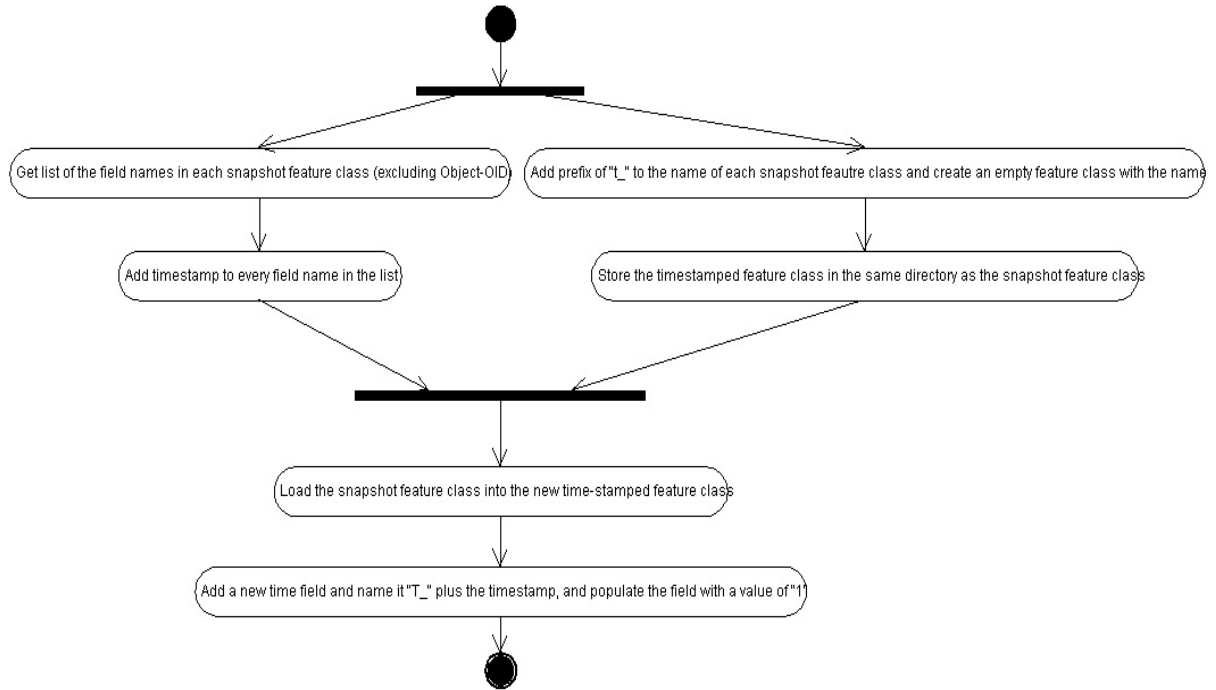
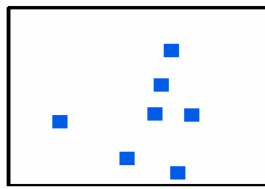


Figure 5.8: A Programming Flow for Time-stamping Snapshot Feature Classes

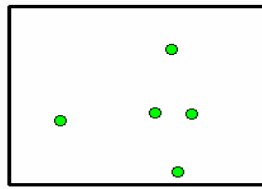
could be embedded into the ArcGIS ArcMap GUI as a button tool (see Figure 5.5). The rest of Figure II.1 also exemplifies ICommand's relationships with several subroutines from the VB project, i.e., how subroutines in ICommand (as a class module) make procedural calls to subroutines in Basic Settings (a standard module).

5.2.2 Generating STComposite Classes

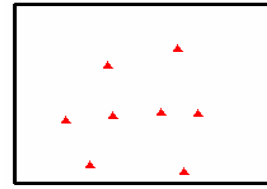
Different geometric features (i.e., points, lines, and polygons) require different procedures for creating the space-time composite (STComposite) feature classes. For example, Figure 5.9(a) represents the snapshot GIS layers of traffic count stations in three different years (i.e., 1994, 1996 and 1999). In this example, traffic count station #3



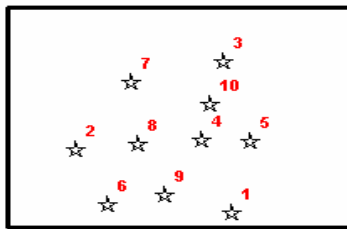
AADT point in 1994



AADT point in 1996



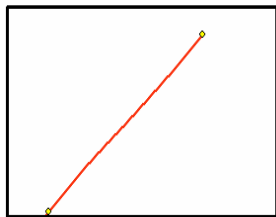
AADT point in 1999



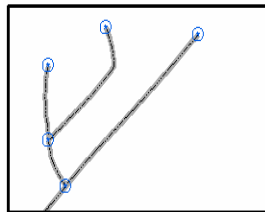
| OBJECTID | T1994 | T1996 | T1999 |
|----------|-------|-------|-------|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 |
| 4 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 |
| 6 | 0 | 0 | 1 |
| 7 | 0 | 0 | 1 |
| 8 | 0 | 0 | 1 |
| 9 | 1 | 0 | 0 |
| 10 | 1 | 0 | 0 |

AADT STComposite point

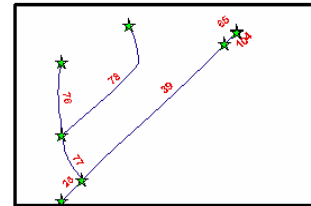
(a) points



road1997 node
road line in 1997

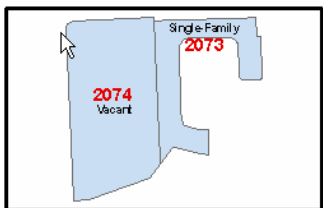


road1999 node
road line in 1999

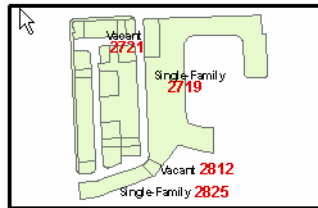


road_97_99 node
STComposite road line

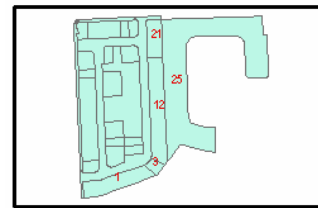
(b) lines



land use polygon in 1998



land use polygon in 1998



STComposite land use polygon

(c) polygons

Figure 5.9: Three Types of Snapshot and STComposite Features

existed in all three years, while traffic count station #9 existed in 1994 only. The STComposite feature class table includes all traffic count stations that existed in 1994, 1996 and 1999. A data value of “1” in the table indicates the existence of a feature at a particular time and a “0” means a feature did not exist at that particular time. As a result, the traffic count station #3 has a value of “1” for T1994, T1996 and T1999, while the traffic count station #9 has a value of “1” for T1994 and 0 for T1996 and T1999.

Creating STComposite feature classes for line and polygon features is more complex than for point features. When we combine multiple snapshot line/polygon feature classes to generate an STComposite feature class, existing lines/polygons may be split or merged to form new features. For example, Figure 5.9(b) shows that combining the road map of 1997 with the road map of 1999 results in an STComposite feature class of new line features. Similarly, polygon features could be split or merged over time as illustrated in Figure 5.9(c). This raises a critical issue of maintaining changes of an object identity over time.

Table 5.2 shows an example of an STComposite feature class table that includes six objects with their unique object identifiers (OIDs), which are 1, 2, 3, 4, 5 and 6. One method of tracking the history of feature changes over time while maintaining their identities is to use the separate OID items (i.e., OID1990, OID1994 and OID1998) in the space-time composite feature class. By comparing the parent OIDs and child OIDs between pairs of consecutive snapshots, we can reconstruct the history of feature changes while maintaining their identities at each snapshot time. For example, a comparison of

Table 5.2: History of Object Identity (OID) Changes in an STComposite Feature Class

| OID | OID1990 | LU1990 | T1990 | OID1994 | LU1994 | T1994 | OID1998 | LU1998 | T1998 |
|-----|---------|--------|-------|---------|---------------|-------|---------|---------------|-------|
| 1 | 1074 | Vacant | 1 | 2074 | Vacant | 1 | 2721 | Vacant | 1 |
| 2 | 1074 | Vacant | 1 | 2074 | Vacant | 1 | 2716 | Single-Family | 1 |
| 3 | 1074 | Vacant | 1 | 2074 | Vacant | 1 | 2812 | Vacant | 1 |
| 4 | 1074 | Vacant | 1 | 2074 | Vacant | 1 | 2825 | Single-Family | 1 |
| 5 | 1074 | Vacant | 1 | 2073 | Single-Family | 1 | 2719 | Single-Family | 1 |
| 6 | Null | Null | 0 | Null | Null | 0 | 2936 | Commercial | 1 |

OID1990 and OID1994 shows that parcel 1074 in 1990 was split into two parcels with OIDs of 2074 and 2073 in 1994. A second query of the OID1994 against the OID1998 indicates that parcel 2074 in 1994 was further split into another four parcels of 2721, 2716, 2812 and 2825. In addition, parcel 2073 changed its OID to 2719 and a new parcel 2936 was created. On the other hand, the last object (i.e., OID=6) in the STComposite feature class table indicates that this parcel did not exist in 1990 and 1994 and was created in 1998 with an OID of 2936.

While the above method is feasible to keep track of changes of object identities through time, it becomes inefficient when we need to identify the existence of a particular record in the STComposite feature class table in multiple years. For instance, in order to find out if feature OID 1 existed in all three snapshot years, we need to formulate a query statement with three cursors referencing T1990, T1994, and T1998. This query statement can slow down the search process significantly when dealing with large data sets. To overcome this shortcoming, the Transland design also creates Time and Time2Space object classes as shown in Figure 5.1. The Time object class stores the time instances of all snapshot GIS layers, while the Time2Space object class keeps track of the

relationships between all snapshot time instances and all unique spatial features in the STComposite feature class (see Table 5.3). Both Time object class and Time2Space object class are generated simultaneously with the STComposite feature class via a set of Visual Basic custom programs developed for this project. The Time and Time2Space object classes together facilitate queries of spatial features over time. When they are linked with the STComposite feature class, it is also feasible to query spatial and attribute changes over time.

Table 5.3: Transland Time and Time2Space Object Classes

| TimeOID | Time |
|---------|-------|
| 1 | T1990 |
| 2 | T1994 |
| 3 | T1998 |

(a) Time object class

| Time | OID |
|-------|-----|
| T1990 | 1 |
| T1990 | 2 |
| T1990 | 3 |
| T1990 | 4 |
| T1990 | 5 |
| T1994 | 1 |
| T1994 | 2 |
| T1994 | 3 |
| T1994 | 4 |
| T1998 | 5 |
| T1998 | 1 |
| T1998 | 2 |
| T1998 | 3 |
| T1998 | 4 |
| T1998 | 5 |
| T1998 | 6 |

(b) Time2Space object class

Similar to the description on the procedures of time-stamping snapshot feature classes, Figure II.2 in Appendix II lays out VB project components for generating STComposite feature classes. The rest of this section will discuss *DoSTComposite*, a subroutine generating STComposite feature classes, and *Layer2STComposite*, a subroutine used within *DoSTComposite* to reflect differences when *DoSTComposite* processes features from point, line, and polygon feature classes. A UML activity diagram in Figure 5.10 describes *DoSTComposite*. The yellow box in the middle of Figure 5.10 indicates where *Layer2STComposite* is executed. Figure 5.11 gives a detailed description of *Layer2STComposite*. This subroutine consists of three activities (with yellow-coded color) that use *CompositePointFeature* (see Figure 5.12) and *SplitLineFeature/SplitPolygonFeature* (see Figure 5.13), respectively. They are subroutines embedded within *Layer2STComposite* with different methods to handle point, line, and polygon features. A program flow for the above VB subroutines is described below.

DoSTComposite → *Layers2STComposite* → *CompositePointFeatures* or
→ *SplitLineFeature/SplitPolygonFeature*

DoSTComposite in Figure 5.10 starts with selecting the first two time-stamped snapshot feature classes for STComposite feature class. After this step is finished, it then checks if there are other time-stamped feature classes left for processing. If yes, it generates another updated STComposite feature class by combining the current STComposite feature class with the available time-stamped feature classes. The loop stops when all time-stamped feature classes have been processed. The subroutine then

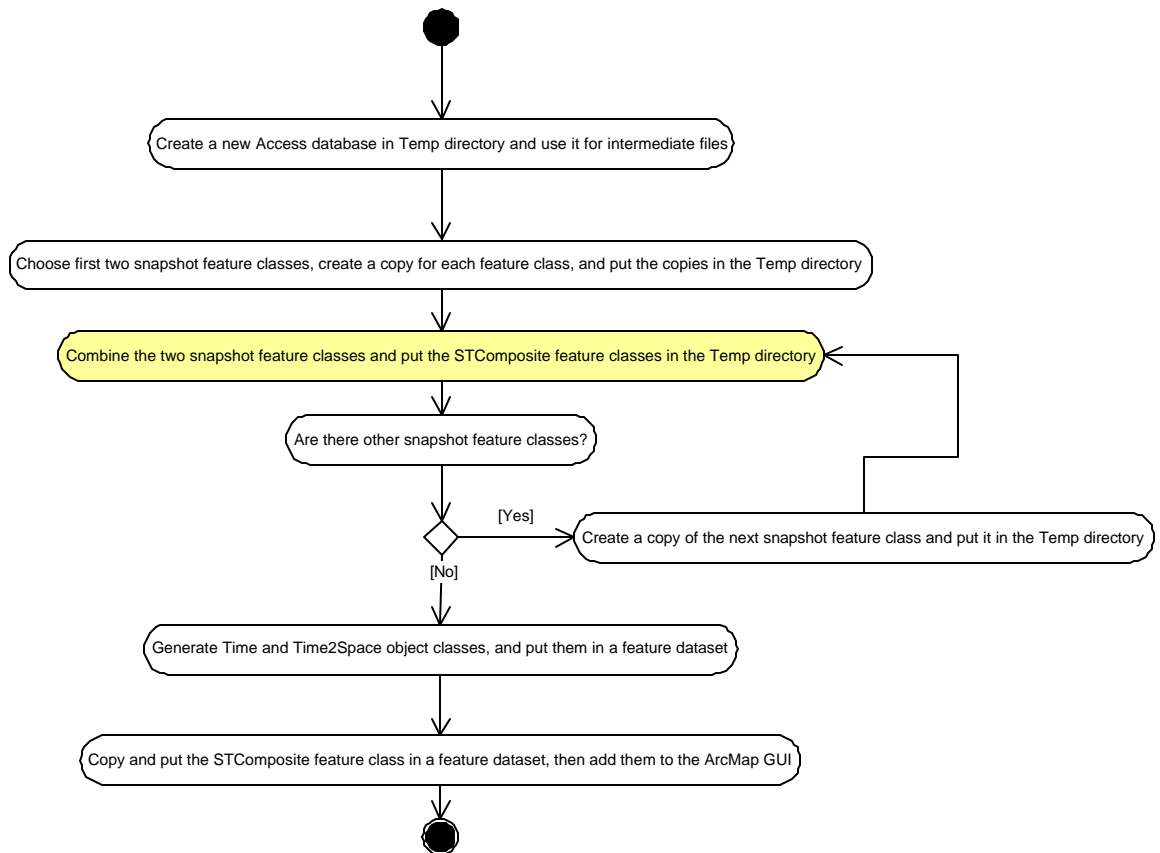


Figure 5.10: A UML Activity Diagram for *DoSTComposite*

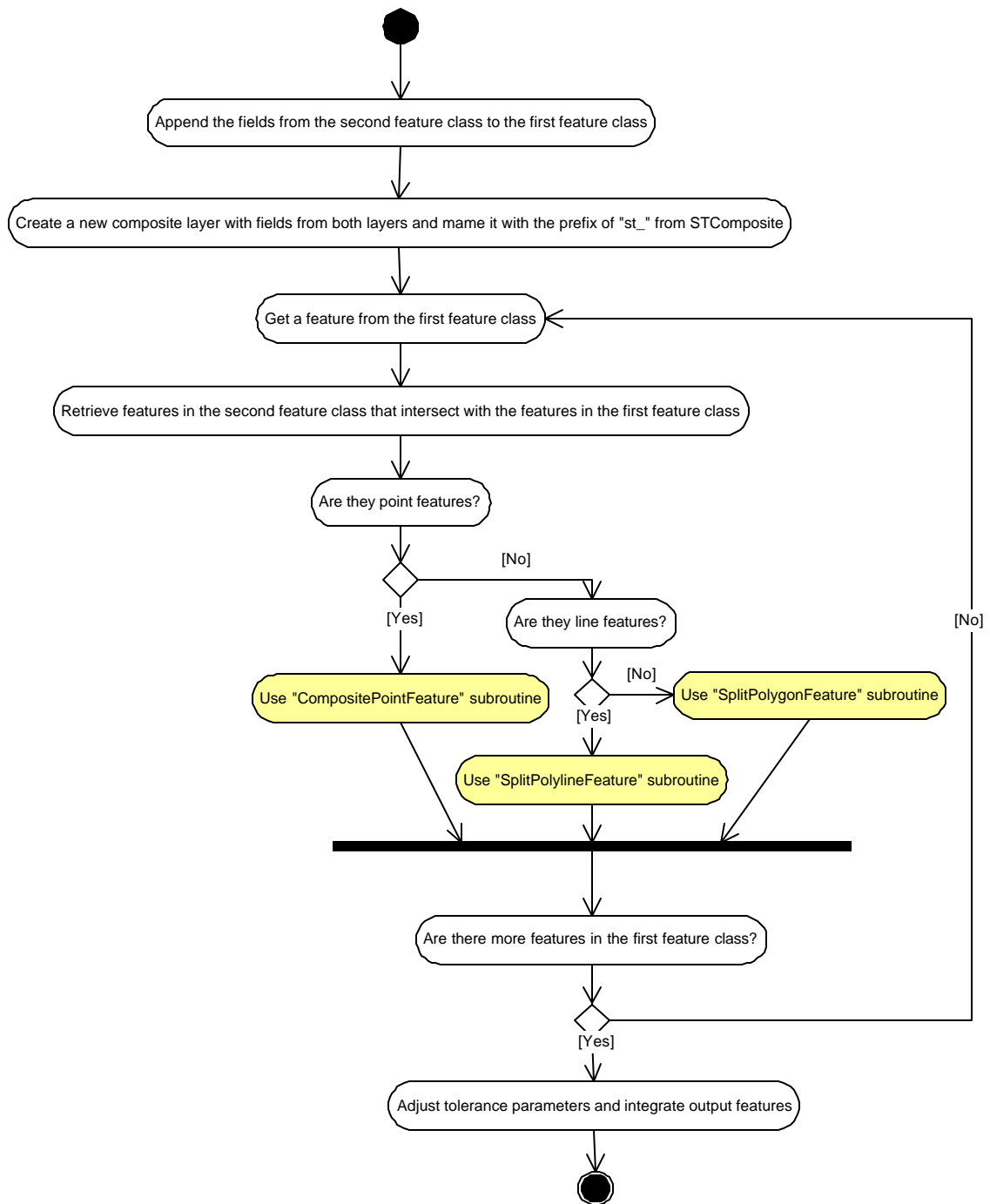


Figure 5.11: A UML Activity Diagram for *Layer2STComposite*

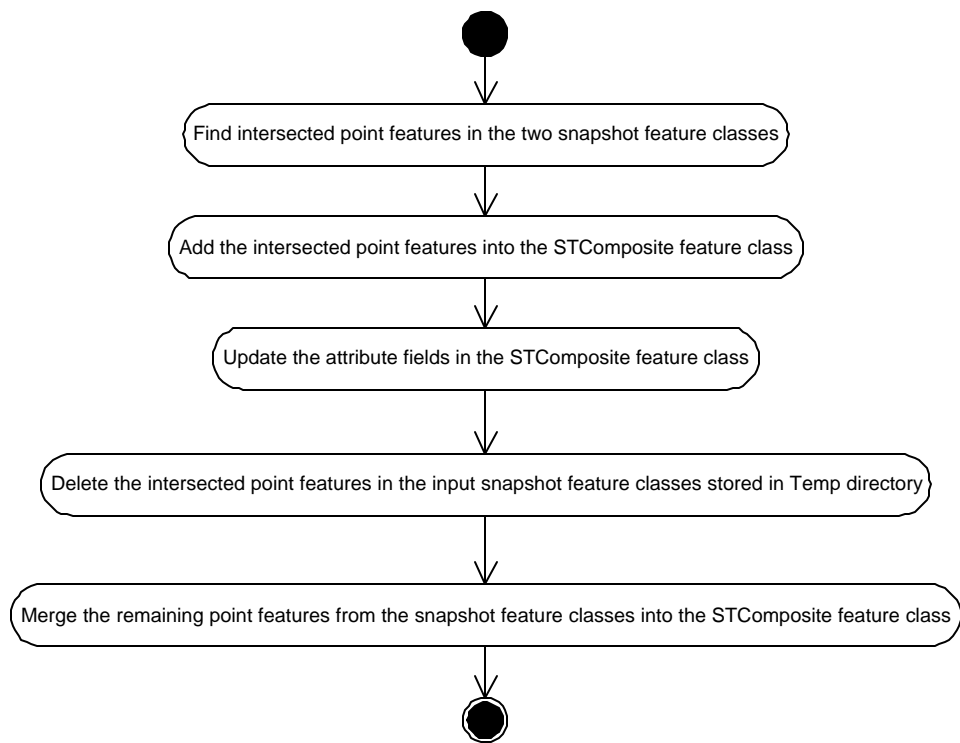


Figure 5.12: A UML Activity Diagram for *CompositePointFeatures*

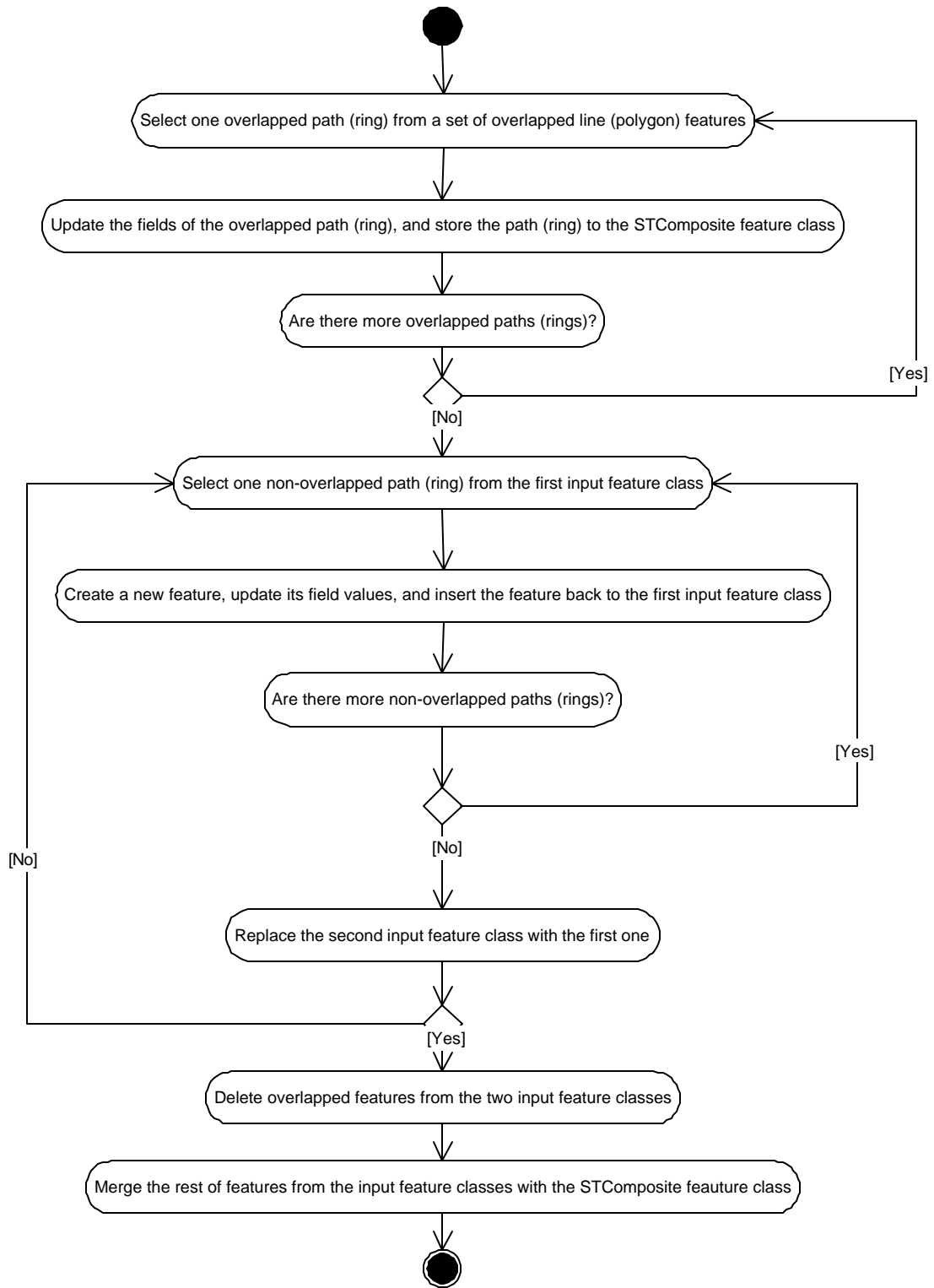


Figure 5.13: A UML Activity Diagram for *SplitPolylineFeature* and *SplitPolygonFeature*

creates Time and Time2Space object classes from the final STComposite feature class. For example, three time-stamped snapshot feature classes of L1, L2, and L3 are used to generate an STComposite feature class. The first loop will involve L1 and L2 to generate an STComposite feature class of STC1. Then, STC1 and L3 are combined in another loop to generate STC2. Time and Time2Space object classes are then derived from the final STComposite feature class of STC2.

Layer2STComposite shown in Figure 5.11 is a subroutine called from *DoSTComposite* when two feature classes, such as L1 and L2, are selected to generate an STComposite feature class. *Layer2STComposite* compares features from the two input feature classes and checks if the intersected features are “permissible intersection” or “non-permissible intersection.” The intersected features are defined as “permissible intersection” when they have the same dimension as the input feature classes. For example, intersected features of points can only be points, which are “permissible intersected” features. However, line and polygon features are different from point features when they are intersected. Intersected features of two line features (1-dimension) may be points (0-dimension) or lines (1-dimension). Intersected features of two polygon features (1-dimension) may be points (0-dimension), lines (1-dimension), and polygons (2-dimension). Figure 5.14 depicts these cases of feature intersections for lines and polygons. It shows only the intersected features as lines for line feature classes and polygons for polygon feature classes are considered as “permissible intersection” features.

| Permissible Intersections | Non-permissible Intersections | |
|---------------------------|-------------------------------|--|
| | | |
| | | |

Figure 5.14: Examples of “Permissible Intersection” and “Non-permissible Intersection” Features

According to the above definition, all intersected point features are always “permissible intersection”. They can be directly added to the STComposite feature class. Line and polygon “permissible intersection” features are different. Extra steps are needed to detect each permissible intersection feature from the input feature classes. Updates are needed on their attributes such as perimeter and area, whose values are calculated as a ratio of the length (area) of a new feature divided by the length (area) of the original feature. After all features have been processed, two input feature classes plus the last STComposite feature class are merged to form the final STComposite feature class.

An example from Figure 5.14 (the upper left case for lines) including only a blue and a red line is used to illustrate the above discussion. After they are intersected, there appears that a “permissible intersection” feature (2 or b) is generated and the rest of

feature segments are numbered as 1 and 3 (from the blue line) and a and c (from the red line). After the “permissible intersection” feature is added to an STComposite feature class, the rest of feature segments in the two input feature classes are merged into the STComposite feature class. The steps involved in this procedure are shown in Figure 5.15.

| <i>Input feature classes</i> | | <i>Output STComposite feature class</i> | |
|---|-------------------|---|-------------------|
| (1) after Layer2STComposite: | | | |
| Shape | Object Identifier | | |
| Line | 1 | | |
| Line | 2 | | |
| Line | 3 | | |
| Shape | Object Identifier | | |
| Line | a | | |
| Line | b | | |
| Line | c | | |
| (2) “permissible intersection” feature: | | | |
| Shape | Object Identifier | Shape | Object Identifier |
| Line | 1 | Line | 4 (2 or b) |
| Line | 3 | | |
| Shape | Object Identifier | | |
| Line | a | | |
| Line | c | | |
| (3) after merging | | | |
| | | Shape | Object Identifier |
| | | Line | 4 (2 or b) |
| | | Line | 1 |
| | | Line | 3 |
| | | Line | a |
| | | Line | c |

Figure 5.15: An Example of Generating STComposite Feature Classes

5.2.3 Implementing the Transland Scenarios

The Transland scenarios, as mentioned previously, portray various spatial and temporal patterns of land use-transportation interaction. GIS software handles the scenarios related to the spatial patterns with spatial/attribute queries. For example, Figure 5.16 shows two dialog windows, implemented for the Transland spatio-temporal data model to identify the spatial patterns using the spatial and/or attribute components. The one at the left is for attribute queries and the one at the right for spatial queries.

GIS software, built upon spatial data models, does not provide query and display functions for analyzing temporal patterns. For example, the dialog windows in Figure 5.18 do not include temporal queries. The Transland spatio-temporal data model implements queries for the temporal component using time instants and time intervals (see the temporal dialogue windows in Figure 5.17). The dialogue window on the left is for time instants and the one on the right for time intervals. Both temporal and spatial

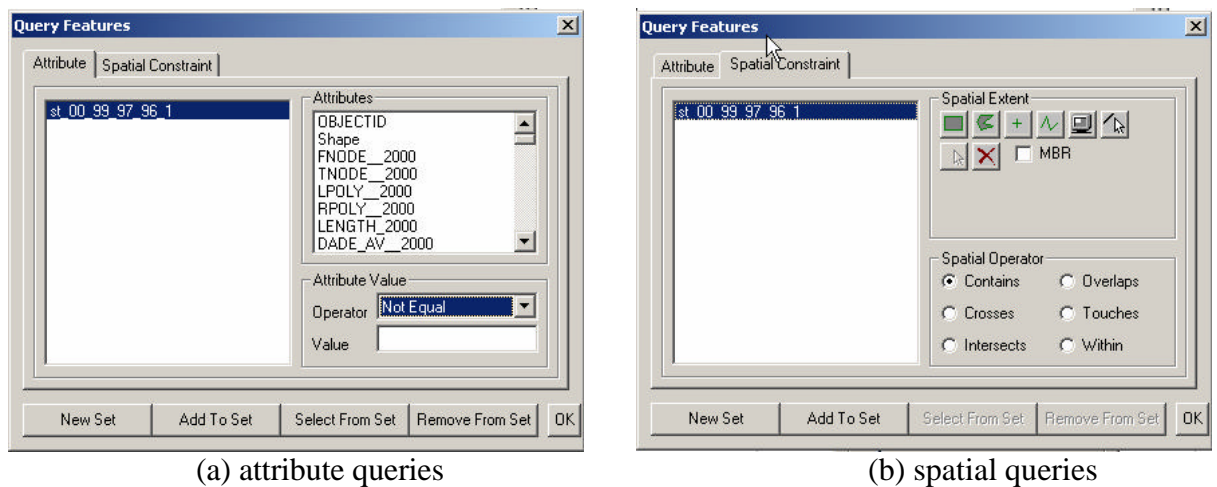
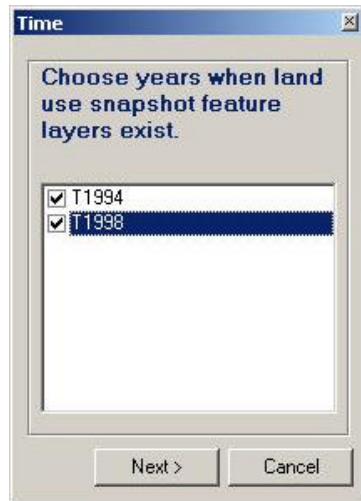
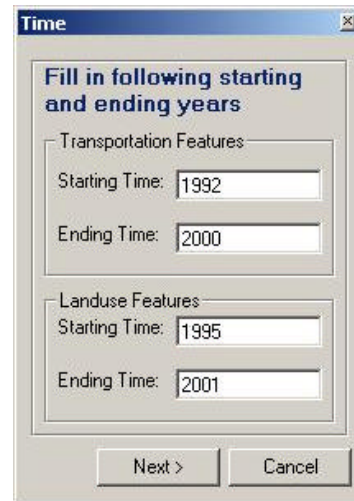


Figure 5.16: Transland Attribute/Spatial Query Tool Windows



(a) time instant queries



(b) time interval queries

Figure 5.17: Transland Temporal Query Tool Windows

queries are essential for the scenario implementation. They are not completely separated from each other. Associations between them are crucial for the implementation of the Transland scenarios.

The Transland scenarios cannot be implemented until the Transland classes are created and ready for use. The previous sections have covered the procedures of creating the Transland classes. As a review, the Transland classes consist of snapshot feature classes, STComposite feature classes, Time object classes, Time2Space object classes, and semantic classes. All of the classes are created for both transportation and land use data sets. The following sections will use UML collaboration and activity diagrams to illustrate the procedures of implementing the Transland scenarios.

5.2.3.1 Using UML Collaboration Diagram to Implement Transland Scenarios: An Example of Scenario 1

This section provides procedural details on steps involved for implementing scenario 1. Similar procedures could be applied for other scenarios. Main differences are the components that are used to fix, control, and measure interactions between land use and transportation over space and time.

Table 5.4 exemplifies a question from scenario 1. The question is decomposed into multiple analysis steps, with the Transland classes related to each step. For example, in step 2, TIPs or transportation features could be identified through TIP semantic classes and transportation STComposite feature classes. Similarly, the rest of steps in Table 5.4 are also related to the other Transland classes.

Table 5.4: Analysis Steps for Transland Scenario 1

| <i>Scenario 1 example: When did major land developments take place within a one-mile zone of I-595?</i> | |
|---|--|
| Steps | Transland Classes Related to Each Step |
| 1) Choose scenario 1 | List of all six scenarios |
| 2) Choose TIPs or transportation features | A list of TIP semantic class and a list of all transportation STComposite feature classes included in ArcMap |
| 3) Specify spatial extent and/or attribute query | Selected TIP semantic classes or selected features from transportation STComposite feature classes |
| 4) Specify land use data fields to be included in the analysis | Land use STComposite and snapshot feature classes within the constraints specified in step 3 |
| 5) Generate final display and summary report | Land use snapshot, STComposite, Time and Time2Space classes |

A UML collaboration diagram in Figure 5.18 describes how the Transland classes used in Table 5.4 are associated with each other. The UML collaboration diagram can be compared with the UML sequence diagram in Figure 5.2. While the sequence diagram describes dynamic interaction among classes in terms of message exchanges over time, the collaboration diagram represents static and dynamic interactions between classes as a series of sequenced messages. It starts from an end user who makes a request from a GUI with two options: semantic TIP classes or street STComposite feature classes. If the user selects from a list of the semantic TIP classes, the GUI then provides the users with a search operation to delineate a spatial extent of searching for land use features from their snapshot and STComposite feature classes and to select their attributes. If a choice is made with the street feature class, the user defines an area of interest. Figure 5.18 reveals the divergence for the choice of TIP classes and STREET feature classes and the convergence after selecting the land use STComposite and snapshot features through the distance search operation. A final report is a collection of the attributes of the features included within the search distance area. Appendix III shows an example of the final report in both map and tabular formats.

GUI screen-captures in Figure 5.19 illustrate GUI tool windows implemented for handling questions arising from scenario 1. Figure 5.19(a) through Figure 5.19(e) are arranged based on a sequence of the steps in Table 5.4. Figure 5.19(a) provides users with scenario options. Figure 5.19(b) then prompts a selection between TIP (from TIP feature classes) and transportation features (e.g, from STREET STComposite feature classes). Figure 5.19(c), equipped with attribute/spatial query functions, specifies areas

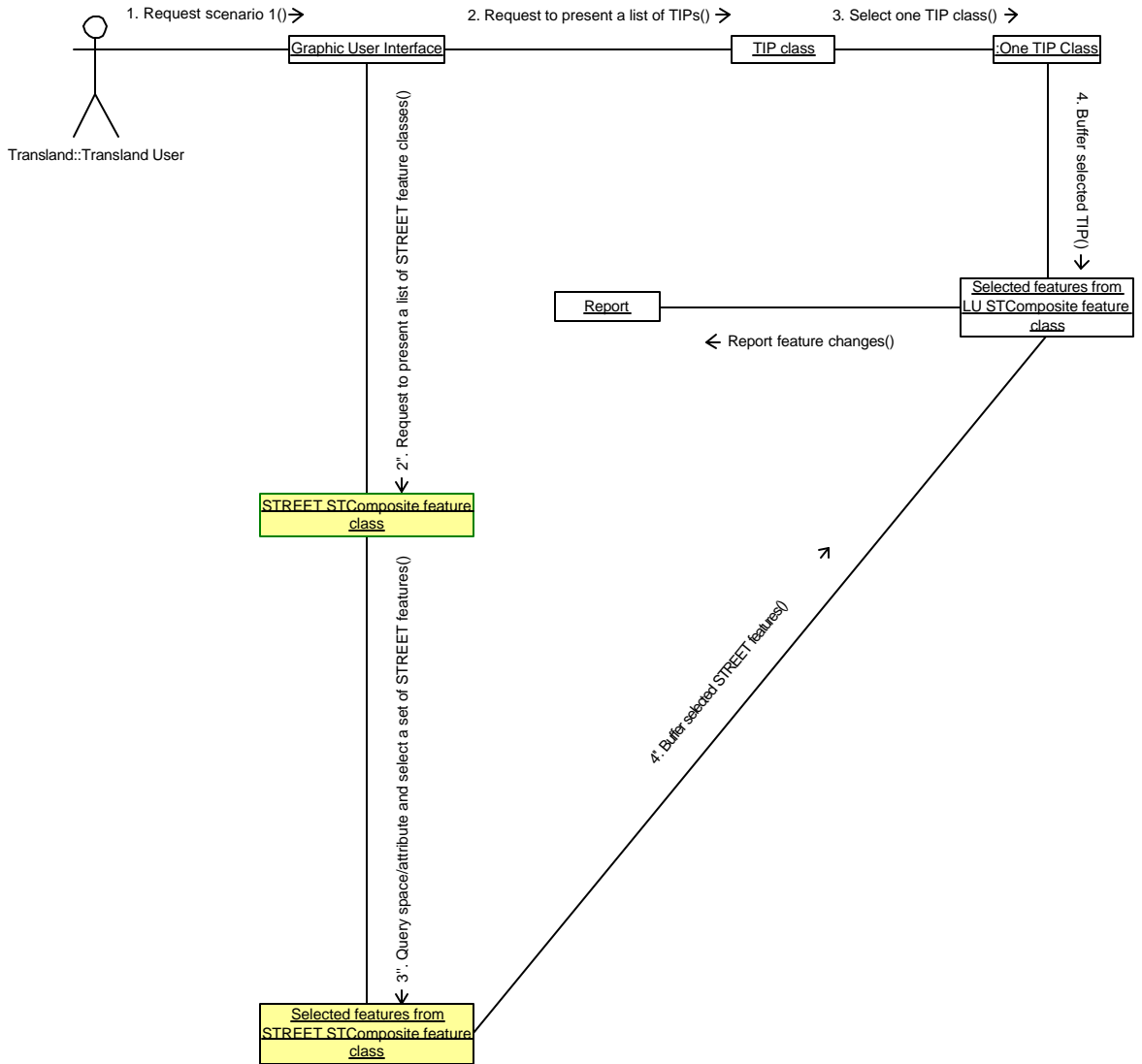
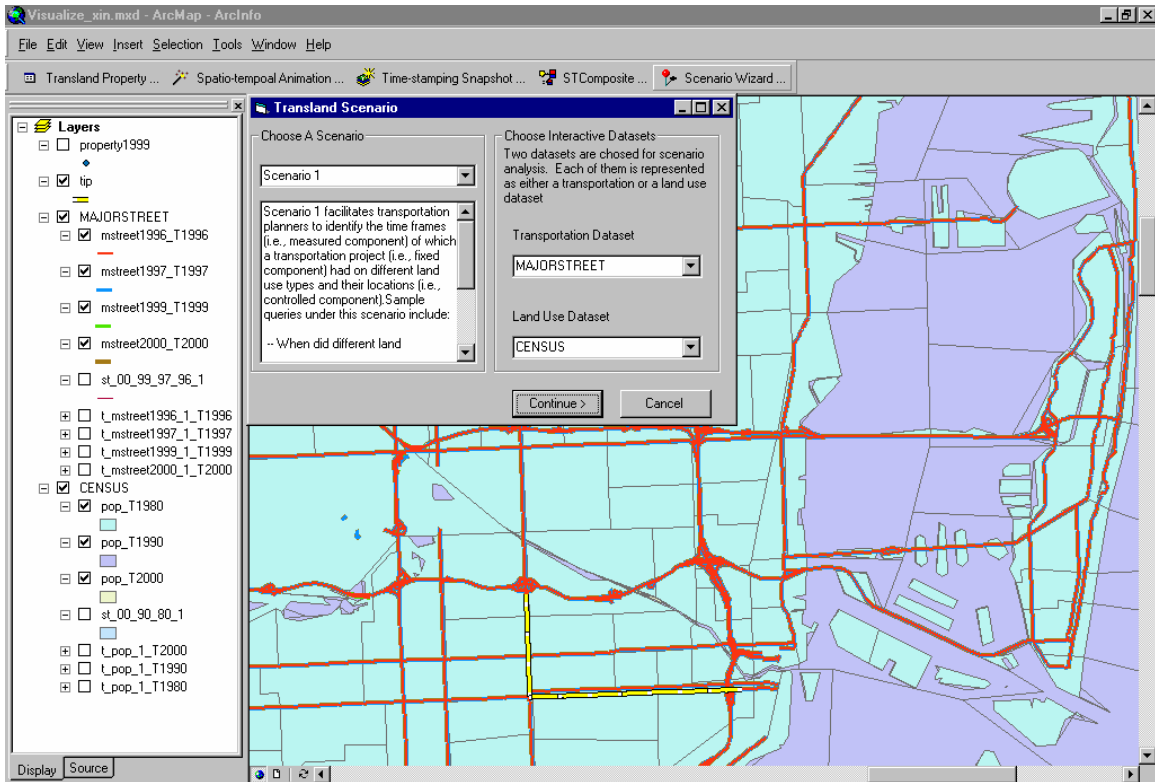
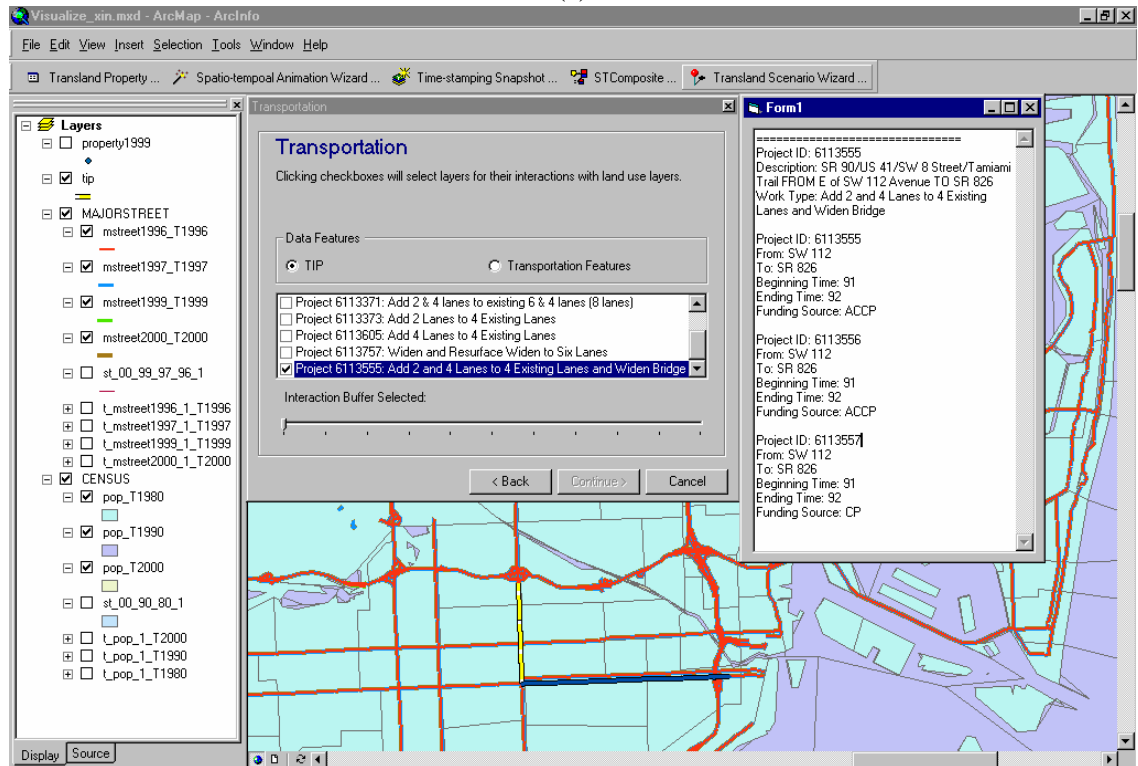


Figure 5.18: An UML Collaboration Diagram for Scenario 1

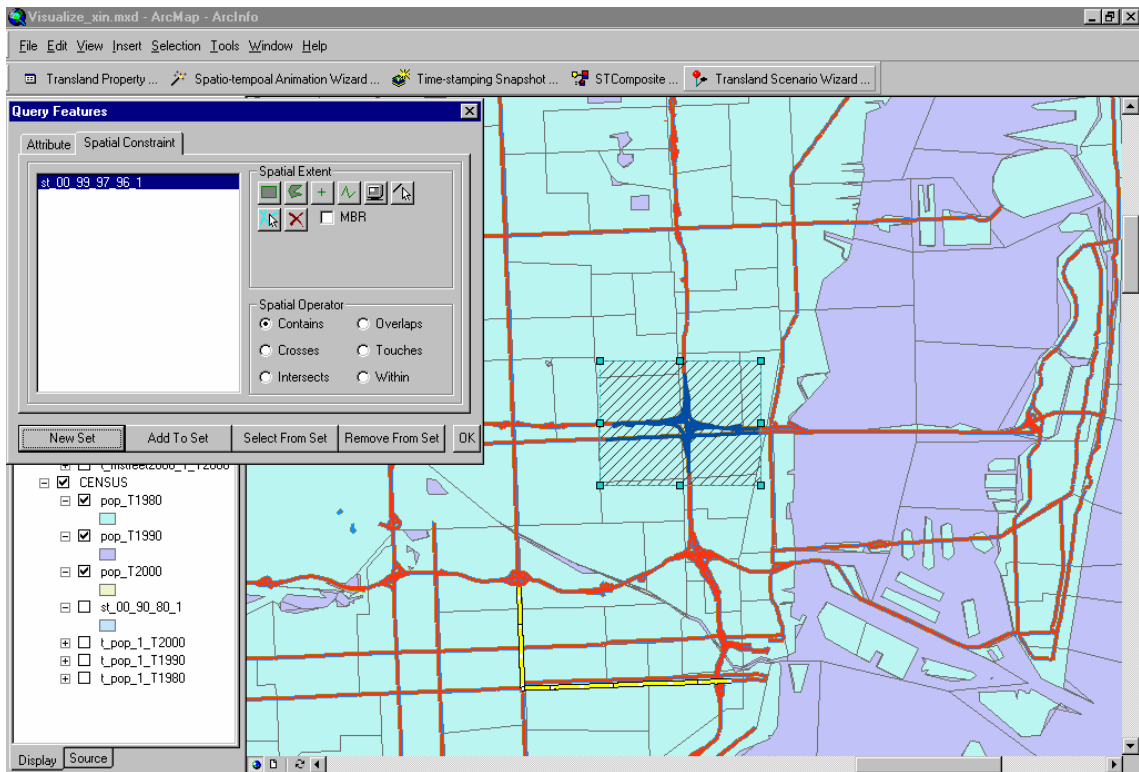


(a)

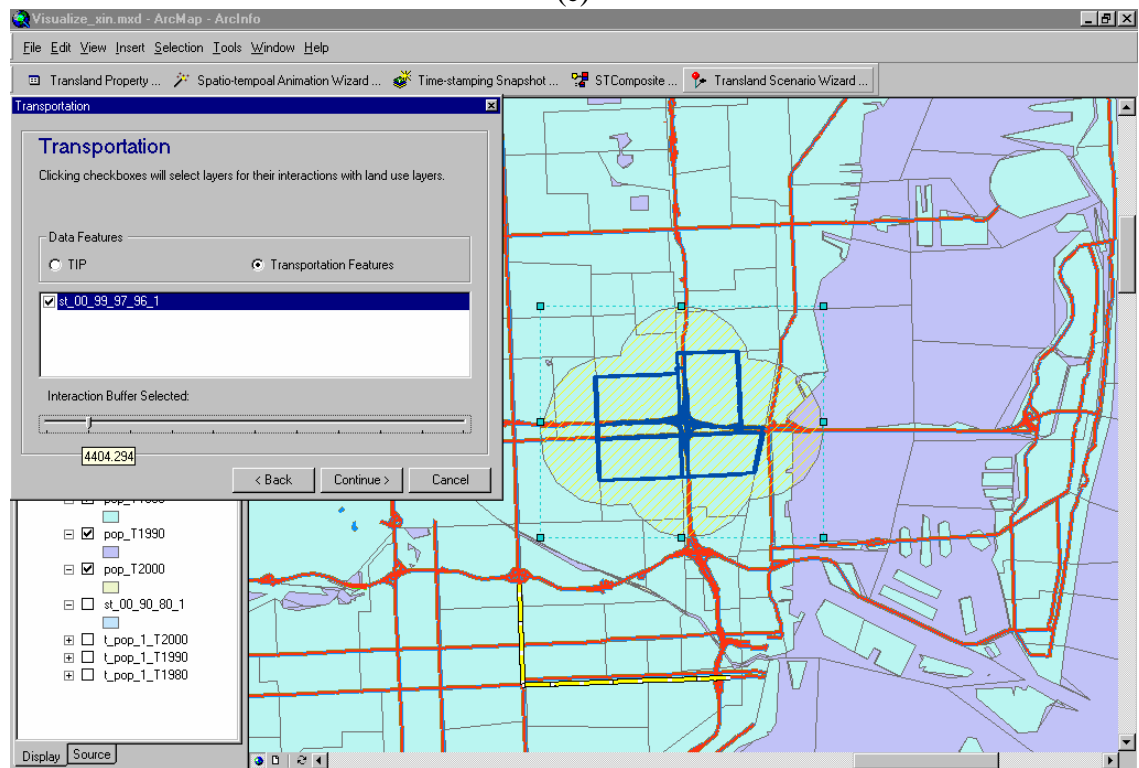


(b)

Figure 5.19: Scenario 1 Screen-captures

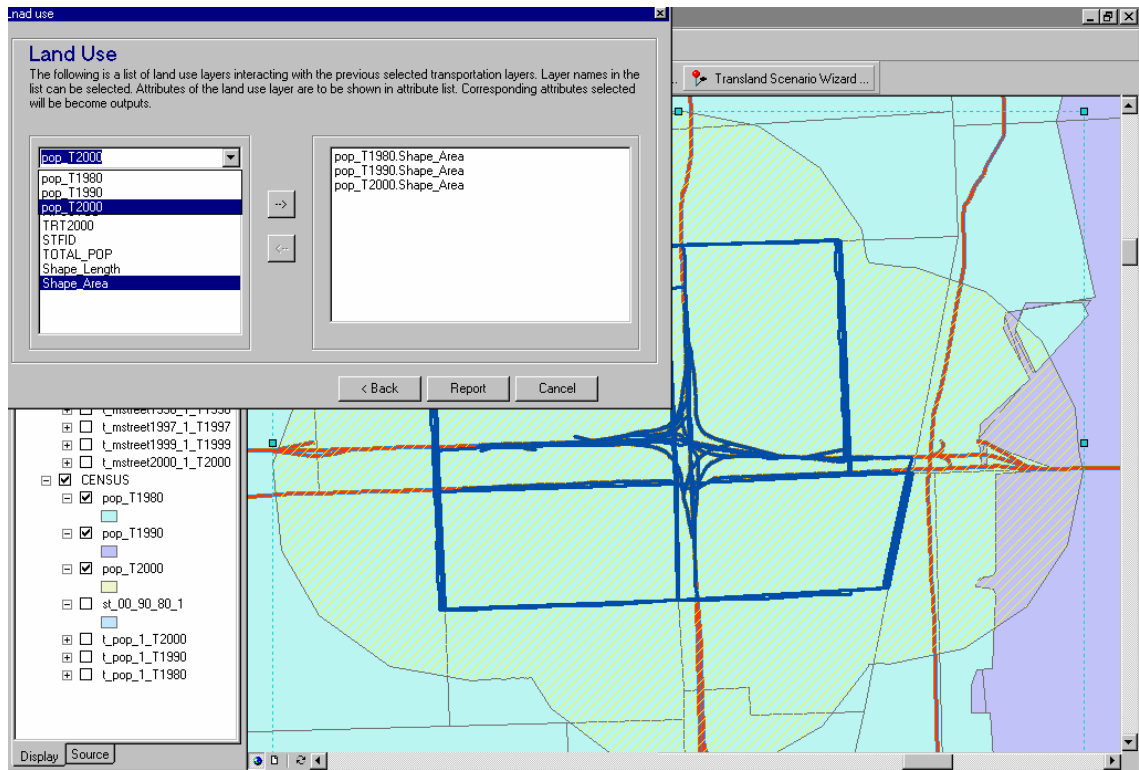


(c)



(d)

Figure 5.19: Continued



(e)

Figure 5.19: Continued

of interest (AOI) based on the above transportation features. Figure 5.19(d) subsequently defines land use interaction areas along transportation AOIs. Finally, Figure 5.19(e) selects attribute items to be included in a report of temporal patterns for land use changes. Appendix IV includes examples and their collaboration diagrams for the five other Transland scenarios.

5.2.3.2 Using Activity Diagrams to Implement the Transland Scenarios

UML activity diagrams illustrate the dynamic nature of an application by modeling the flow of control among activities. An activity represents an operation on

some classes in an application that changes the state of the application. Figure 5.20 is a UML activity diagram depicting an operational flow for implementing the Transland scenarios. The operational flow is represented and implemented with Visual Basic forms, such as “time form”, “distance search form”, and “report form” (see Figure II.3 in Appendix II). The “time form” (see Figure 5.17) corresponds to the time component and its GUI consists of custom controls for defining time instants and intervals. The “distance search form” (see Figure 5.19(d)) has a collection of controls engaging feature selection and subsequent search distance for land use-transportation interaction. The “report form” is to report the attributes relevant to features that are within the distance search area. For example, if “distance search form” indicates that the street (transportation category) feature class is selected, attributes on the “report form” are from the land use data, such as census tract feature classes. Placing the “time form” before or after the “distance search form” will determine the type of scenarios. Scenarios 1, 2, 5, and 6 use the “distance search form” first and then the “time form.” They are different from the other two scenarios (scenarios 3 and 4) because they treat time as a non-fixed component. These four scenarios treat time either as the measured component (scenarios 1 and 5) or as the controlled component (scenarios 2 and 6). In contrast, scenarios 3 and 4 place the “time form” prior to the “distance search form.” Therefore, they explore transportation and land use interaction by treating time as the fixed component.

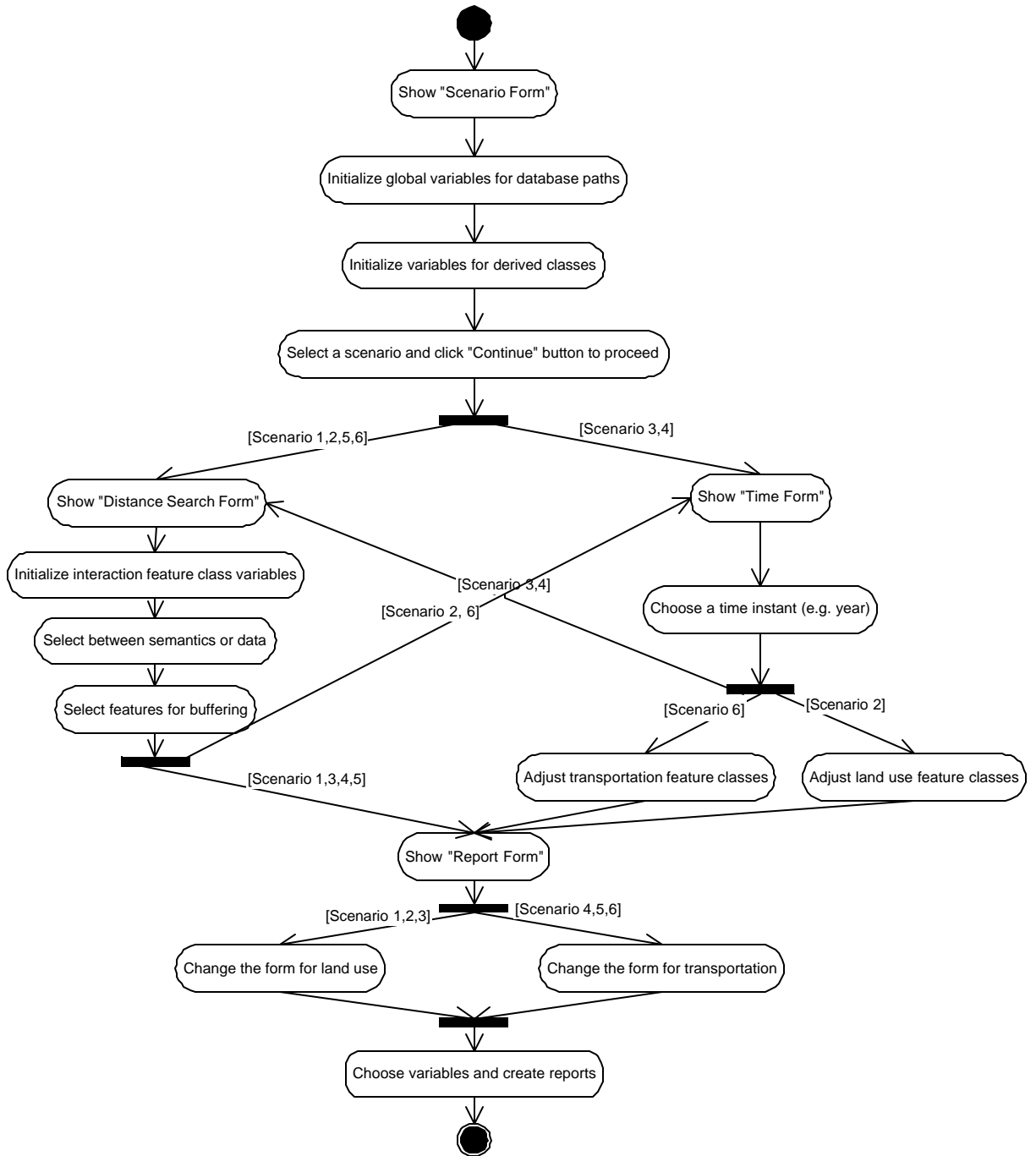


Figure 5.20: An UML Activity Diagram for Implementing the Transland Scenarios

5.3 Summary

The Transland scenarios illustrate that time, transportation, and land use are the three major components of a framework, which is used to explore the interaction between transportation and land use. The design of the Transland spatio-temporal data model defines the Transland classes in correspondence with these three components. The Transland classes consist of the snapshot and semantic classes, along with the STComposite and time classes derived from the snapshot classes. Managing these four classes is one of the major tasks the Transland data model attempts to accomplish. ArcCatalog provides an object-relational Access DBMS for the storage and retrieval of the Transland classes. A GUI built within ArcMap includes a set of controls for generating, analyzing, and visualizing the Transland classes. ArcMap GUI also serves as a place for assembling the scenarios from the Transland classes.

Unified Modeling Language is applied not only for the design of the Transland spatio-temporal data model in Chapter 4, but also for documenting the procedures of its implementation in this chapter. The class diagram contributes to outlining a conceptual framework of spatio-temporal classes and the Transland scenarios. These classes are generated from spatial classes available in the ArcGIS data model. Sequence and collaboration diagrams, on the other hand, help illustrate the design and implementation procedures.

6 CONCLUSIONS

Land use and transportation interaction has been a major research topic for several decades. Many theories and models are suggested to study this well-known, yet complicated, process. The use of confirmatory analysis approaches based on prior theories and models certainly has helped us gain some insights into the complex process of land use and transportation interactions. However, empirical studies suggest that land use and transportation interaction patterns can be highly variable between geographic areas. Each geographic area tends to have its own unique characteristics that could lead to a different pattern of land use and transportation interaction. The interaction patterns also are likely to vary as we examine them at different spatial and temporal scales. As geographic processes often exhibit properties of both spatial dependency and spatial heterogeneity, our challenge is to identify the spatio-temporal patterns underlying these complex geographic variations.

There exists a need for proposing spatio-temporal data models capable of storing, modifying, and querying historic data revealing spatio-temporal patterns from land use-transportation interaction. Even though many researchers are interested in this topic, their impact to commercial DBMSs that facilitate spatio-temporal data models is negligible since research on spatio-temporal data models fails to provide ready solutions for a wide range of implementation. There are a series of unsolved issues related to the spatio-temporal data models. For example, what space and time relationships are to be represented in spatio-temporal data models? Do we need to develop spatio-temporal

query languages and indexing methods? What are the gains and loss of proposing a spatio-temporal data model based on either the spatial extension of a temporal data model or the temporal extension of a spatial data model?

With recent advancements of GIS technology and an ongoing research progress on spatio-temporal data models, we are now equipped with better research tools to tackle complex geographic processes. This dissertation proposes and implements the Transland spatio-temporal data model, coupled with an exploratory analysis approach, to allow a systematic and interactive way of analyzing land use and transportation interactions among various data sets and user-selected spatial and temporal scale. The following section sums up the major conclusions and contributions.

6.1 Applying Exploratory Data Analysis Approach for Land Use-Transportation Interaction

Unlike confirmatory approaches that are stated in terms of mathematical concepts and parameters within a simplified real world framework, use of the exploratory data analysis approach in the dissertation makes it feasible to analyze spatio-temporal interactive patterns in a more efficient and effective way than the conventional snapshot GIS approach. Extending Sinton's measurement framework into a spatio-temporal interaction framework provides a systematic means of exploring land use and transportation interaction. Preliminary experiments of data collected from Dade County (Miami), Florida suggest that the temporal GIS-based exploratory analysis system

implemented in this dissertation can help transportation planners identify and visualize patterns of land use and transportation by controlling the spatial, attribute, and temporal elements. Although the identified interaction patterns do not necessarily lead to rules that can be applied to different geographic areas, they do provide useful information for transportation modelers to re-evaluate the current model structure and provide insight on the validity of existing model parameters.

6.2 The Synergy Representation of Space and Time

Orthogonality and synergy are two concepts adopted by researchers for representing space and time. Orthogonality requires that spatial and temporal functions are developed independently. Synergy means that a system gains performance from the combined use of the functionalities provided from spatial and temporal dimensions. Most GIS users are used to the orthogonal concept since it fits into their common thinking pattern that dealing with time in GIS needs only to add a time dimension upon the existing spatial dimension, such as MADS (Parent et al., 1999). On the other hand, the synergy concept states that space and time are not separable dimensions. Actually, the synergy concept reflects the true nature of space and time, which is that they are inseparable. The literature review of spatio-temporal data models also indicates that many studies concentrate on the synergy concept, such as ESTDM (Peuquet and Duan, 1995), STComposite data model (Langran, 1989 and 1992), Worboys data model (Worboy, 1992b), and Object-Oriented Data Model (Wachowicz, 1999).

Synergy-based ADT are easy to design but hard to implement due to their need for object-oriented implementation environment, which has not been available to GIS. Nevertheless, synergy and its realistic reflection on space and time are alternatively implemented in relational DBMSs as STComposite objects (Yates and Chrissman, 1993; Raza and Kaina, 1998) and a semantic domain (Yuan, 1996 and 1999). Their research indicates some important considerations in the design and implementation of the Transland spatio-temporal data model. STComposite and semantic data types are synergy-based. The Transland spatio-temporal data model uses them to represent the inseparable behavior between space and time for land use-transportation interaction. The STComposite data types are generated from a set of snapshot data types, with STComposite spatial units carrying attributes from the different time periods of the snapshot data type. The dissertation also includes orthogonality-based data types, like snapshot and time data types. They exist to support the synergy-based data types with respect to their generation and query operations.

6.3 Unified Modeling Language for the Design and Implementation of the Transland Spatio-Temporal Data Model

ESRI ArcGIS data model provides GIS users with the ability of creating custom objects. The custom objects created for the Transland spatio-temporal data model are grouped into the snapshot feature classes, the STComposite feature classes, the semantic classes (including feature classes and object classes), the Time object classes, and Time2Space object classes. The Transland spatio-temporal data model requires these

custom objects to be combined with spatial objects from the ArcGIS data model to not only feature time-varying spatial data types, but to preserve spatial queries and indexing functions as well. This is an approach the dissertation takes to develop the Transland spatio-temporal data model by making use of what a spatial data model can provide for time-varying spatial data. There are many spatial objects, as well as UML class diagrams with the layout for the spatial objects, which are available from the ArcGIS data model, and they allow users to develop their own data models. As shown in Chapter 4, the UML class diagrams play an important role for illustrating the custom objects of the Transland spatio-temporal data model and their relationships with the embedded spatial objects.

Besides the class diagram, sequence, collaboration, and activity diagrams are the three other types of UML diagrams presented in Chapter 5 to list user operations and pass messages, which are closely related to the graphic user interface (GUI) controls, among the custom objects. The sequence and collaboration diagrams illustrate how the user operations are implemented as GUI controls from different angles. The sequence diagrams reveal the dynamic order of the controls, but their detailed static associations have to rely on the collaboration diagrams. That is why the collaboration diagrams, not the sequence diagram, are used to depict procedures of organizing the custom objects for the scenario questions. The activity diagrams, equivalent to flow charts for procedural programming, perform in the same way to illustrate logic flows for object-oriented programming.

6.4 Implementing the Transland Spatial Data Model Using ESRI COM-compliant ArcObjects

The Transland spatio-temporal data model is implemented with ESRI ArcObjects COM, an object-oriented programming platform accompanying the ESRI ArcGIS Object Model. The purpose of the implementation is to demonstrate how the ArcObjects COM has spatial objects with their functions exposed to generate spatio-temporal objects, which follow the design from UML discussed above. COM compliant languages (e.g., Microsoft C++, Microsoft Visual Basic, and Delphi) can gain access and use the spatial objects of ArcObjects COM for developing custom programs. The Transland spatio-temporal data model uses Microsoft Visual Basic to implement a prototype of the Transland spatio-temporal data model. The final product of the Transland spatio-temporal data model is a GIS application with Transland database managed through ArcGIS's ArcCatalog and with the Transland GUI embedded within ArcMap. The Transland database, developed as an Access Personal Geodatabase operated through ArcCatalog, exchanges data with the Transland GUI in ArcMap. The GUI retrieves GIS layers and attribute data tables from the database and stores generated spatio-temporal data in the database.

6.5 Future Work

There are many possible areas for future improvements to data model and procedures developed in this study. The spatio-temporal interaction framework offers a

general structure to lead analysts in a systematic manner of exploring land use and transportation interaction. This framework, however, may be too cumbersome for analysts with limited GIS background. Additional custom application tools are needed to make it a more user-friendly system. Integration of existing land use and transportation models into the system will be another improvement. The rich set of temporal GIS databases can be used to generate input data for the existing land use and transportation models. Results from these models can be compared with the interaction patterns identified from spatio-temporal exploratory analyses to validate the models.

The design of the Transland spatio-temporal data model also has room for further improvements. For example, the temporal GIS databases can quickly grow into very large files. This requires innovative approaches to data model design and spatio-temporal analysis procedures to achieve a reasonable performance level.

There arise several problems from the implementation of the Transland spatio-temporal data model. The Transland classes are crucial in the Transland spatio-temporal data model since they explicitly reveal a temporal component based on snapshot-based spatial data models. However, there are shortcomings for these classes. One outstanding problem is that it is hard to keep track of the boundary evolution of a spatial entity. For example, once the STComposite classes are generated from the snapshot classes, their record size might become huge and managing them can be inefficient. The Transland spatio-temporal data model has attempted to preserve the snapshot classes to alternatively provide snapshot information while queries are targeted for the STComposite classes,

which can be cumbersome when dealing with large-sized snapshot classes. Future research proposals could be to use an overlapped B+-trees (OB+-trees) structure and a hash data structure to supplement the Transland derived classes. The current use of relational DBMSs results in data redundancy because both the STComposite and snapshot databases are still maintained. Object-relational Oracle 8i+ allows users to define *Varray* that contains a variable number of ordered elements (Oracle 8i Data Cartridge Developer's Guide, Release 2 (8.1.6), 1999). Therefore, it is at least theoretically possible to implement DT^{ST} using Oracle 8i+, or other DBMSs that provide data types that are similar to *Varray*. The Access personal Geodatabase used for implementing the Transland data model, does not provide data type *Varray*, but it has alternatives for handling DT^{ST} as presented in Chapter 5 in the implementation of the Transland spatio-temporal data model. A further exploration of the STComposite data reveals that it can be decomposed to entail three data types: a semantic data type, time-varying spatial data type, and time data. The semantic data type reflects the rich, but complicated nature, of spatio-temporal data when viewed from the users' perspective. The concept of spatio-temporal data types, elaborated in this dissertation, may not be fully implemented based on object-oriented functions available from ArcGIS Access Personal Geodatabase DBMS. Nevertheless, the extensibility of ArcGIS allows other DBMSs, such as Oracle 8i+, to implement the concepts developed here.

It is hoped that improvements mentioned here will help make spatio-temporal exploratory data analysis a useful approach to studying land use and transportation interactions. No matter what advances are made in the data models and their

implementations, spatio-temporal exploratory data analysis will share the same strengths and weaknesses as other EDA methods. That is, the tools developed here may not yield significant insights into a particular land use-transportation study. However, without them it will be difficult, if not impossible, to fully explore the potential wealth of information to be found in the snapshot databases collected over the past two decades.

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APPENDICES

Appendix I: UML Diagram for ESRI Classes and Interfaces

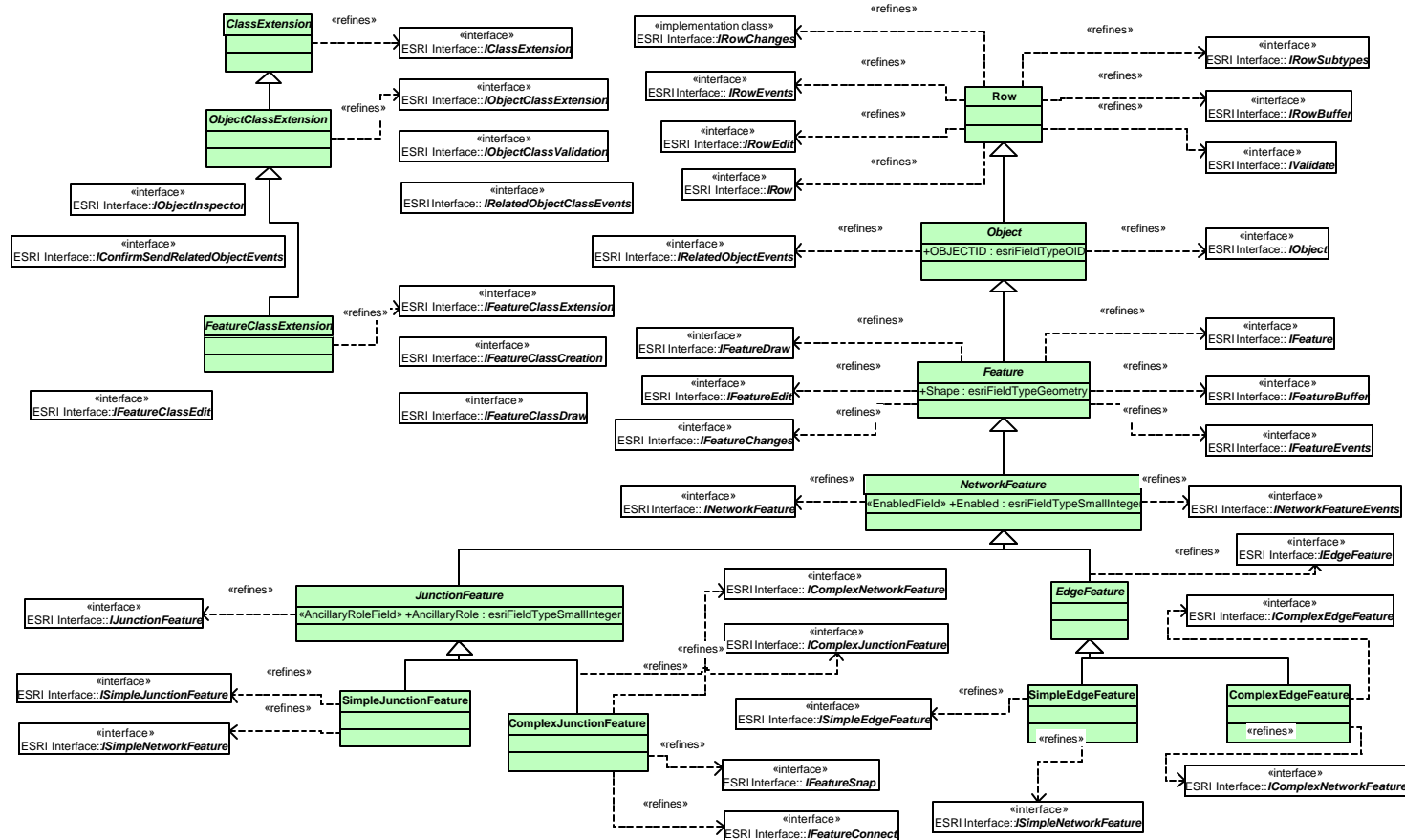


Figure I.1: ESRI Classes (Source: Curton, et al., 2001)

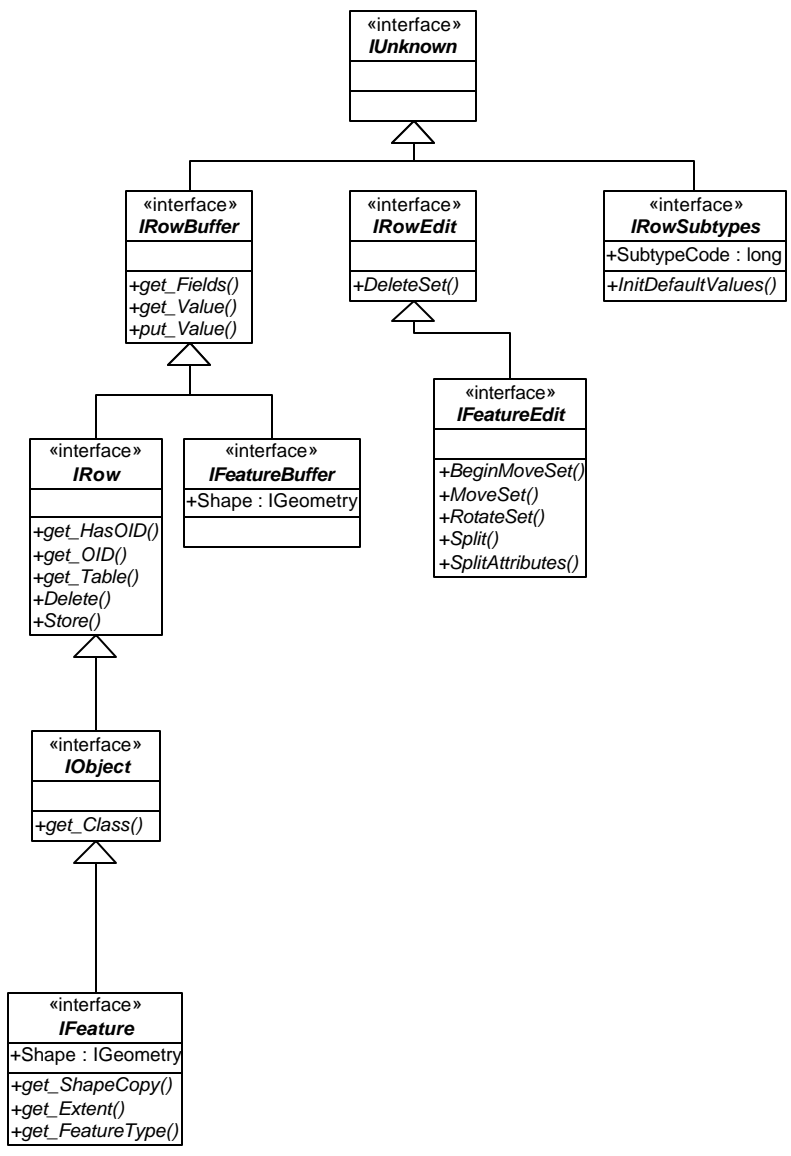


Figure I.2: ESRI Interfaces (Source: Curton, et al., 2001)

Appendix II: Basic Modules for Implementing the Transland Classes and Scenarios

| Form Name | Form Description |
|---------------------|---|
| frmTimestamping.frm | Form for selecting features classes |
| frmResources.frm | Form for defining an icon representing dataPrepare.dll when it is added to ArcMap GUI as a button |

| Module Name | Module Description |
|----------------------|--|
| Basic_Setting.bas | Basic module that dimensions global variables |
| Database_Utility.bas | Module that contains utility subroutines for managing geodatabases |

| Class Module Name | Class Module Description |
|------------------------|---|
| Application_Status.cls | Class module that implements IApplication and IStatusMessage |
| IApplicationStatus.cls | Class module that defines an abstract class which sets a value for <i>Application</i> |
| IStatusMessage.cls | Class module that defines a subroutine for displaying a message |
| Time_Stamping.bas | Class module that implements ICommand and initializes frmPrepare.frm with its OnClick event |

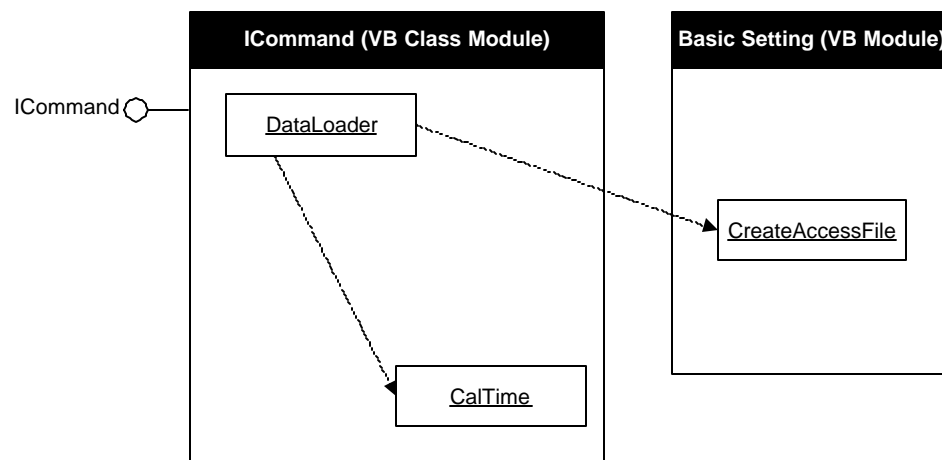


Figure II.1: Visual Basic Subroutines for Time-stamping Snapshot Feature Classes

| Form Name | Form Description |
|--------------------|---|
| frmSTComposite.frm | Form for selecting features classes and providing STComposite-related information |
| frmResources.frm | Form for defining an icon representing dataPrepare.dll when it is added to ArcMap GUI as a button |

| Module Name | Module Description |
|---------------------------|--|
| Basic_Setting.bas | Basic module that dimensions global variables |
| Data_Convert.bas | Module that includes subroutines for converting data between personal geodatabases, coverages, shapefiles, and SDE layers. |
| Database_Utility.bas | Module that contains utility subroutines for managing geodatabases |
| StringParsing_Utility.bas | Module that contains utility subroutines for string parsing. |

| Class Module Name | Class Module Description |
|------------------------|---|
| ApplicationStatus.cls | Class module that implements IApplication and IStatusMessage |
| IApplicationStatus.cls | Class module that defines an abstract class which sets a value for <i>Application</i> |
| IStatusMessage.cls | Class module that defines a subroutine for displaying a message |
| SortedList.cls | Class module that arranges feature layers in a sorted order |
| STComposite.cls | Class module that implements ICommand and initializes frmComposite.frm with its OnClick event |

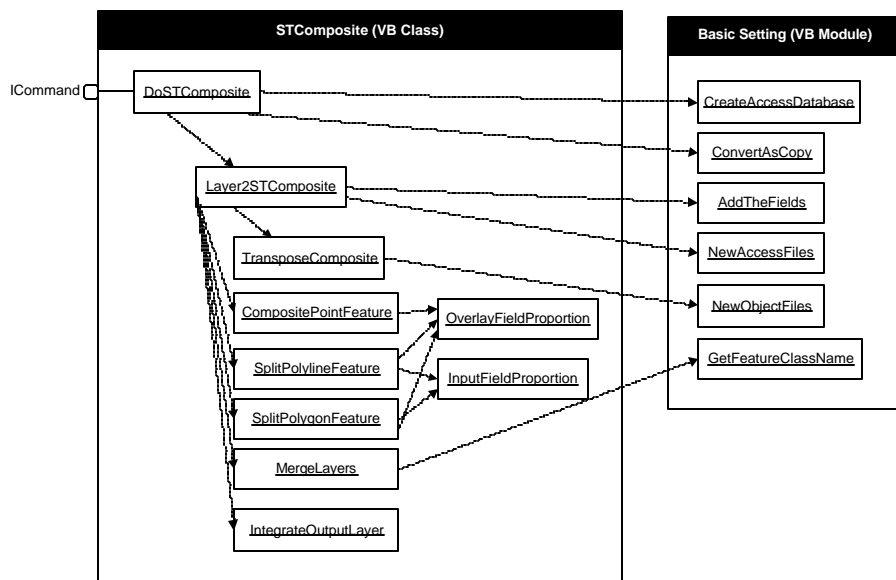


Figure II.2: Visual Basic Subroutines for Generating STComposite Feature Classes

| Form Name | Form Description |
|--------------------------|---|
| frmDescription.frm | Simple form for describing TIPs and land developments |
| frmDistancesearching.frm | Form that defines search distance |
| frmQuery.frm | Form that defines attribute and spatial constraints for queries |
| frmReport.frm | Form that collects attributes for final reports |
| frmResources.frm | Form that defines an icon representing dataPrepare.dll when it is added to ArcMap GUI as a button |
| frmScenario.frm | Simple form for scenario selections |
| frmTime.frm | Form that defines scenario timeframes |

| Module Name | Module Description |
|---------------------------|--|
| Basic_Setting.bas | Basic module that dimensions all global variables |
| Data_Convert.bas | Module that includes subroutines for converting data between personal geodatabases, coverages, shapefiles, and SDE layers. |
| Data_Query.bas | Module that includes subroutines for frmQuery.frm |
| Data_Relate.bas | Module that contains subroutines to establish relationships among feature classes and object classes. |
| Data_Report.bas | Model that contain subroutines for summary reports |
| Data_Scenario.bas | Module that dimensions global variables for scenarios |
| Database_Utility.bas | Module that contains utility subroutines for managing geodatabases |
| Popup_Menu.bas | Module that assists for building right-click context menus |
| StringParsing_Utility.bas | Module that contains utility subroutines for string parsing. |

| Class Module Name | Class Module Description |
|-------------------|---|
| Scenario.cls | Class module that includes subroutine for frmScenario.frm |

Figure II.3: Visual Basic Subroutines for Implementing the Transland Scenarios

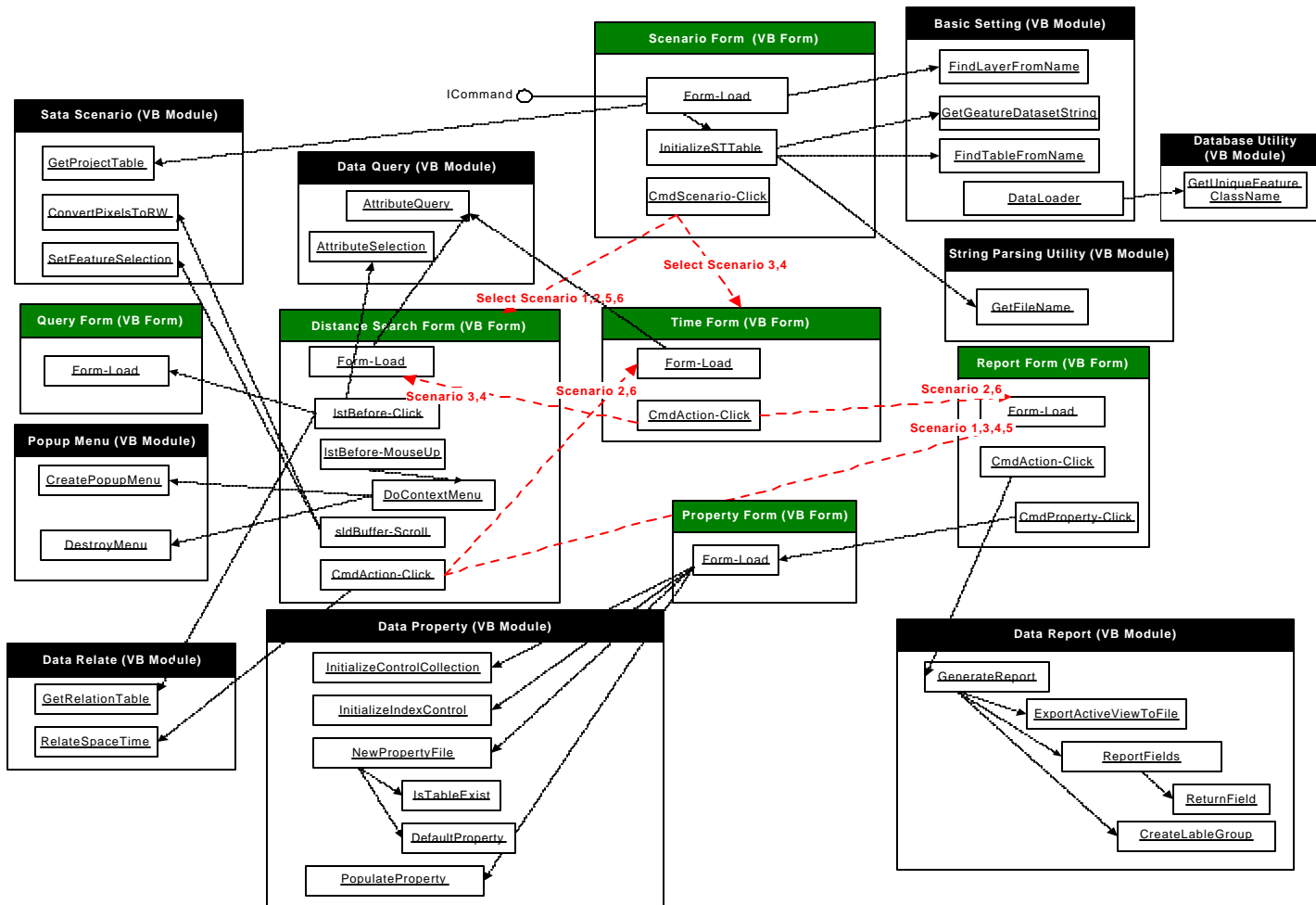
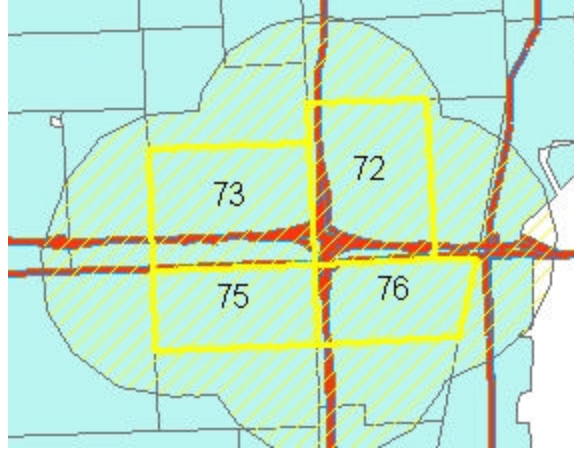


Figure II.3: Continued

Appendix III: A Sample Report for Scenario 1

Transland Summary Report
Scenario 1
(Created: 9/24/2002 12:04:12 AM)

Layer Name: pop_T1980



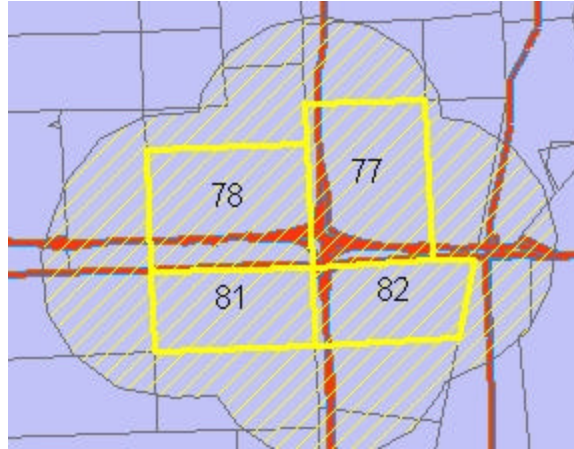
Selected feature values:

| OID | Shape_Area |
|-----|------------------|
| 72 | 21657747.9039008 |
| 73 | 22174761.0782468 |
| 75 | 14450647.3841637 |
| 76 | 13409416.442228 |

Statistical results on the numeral fields of the above table:

| Field Name | Minimum | Maximum | Mean | Standard Deviation |
|--------------------------------------|------------------|------------------|------------------|--------------------|
| Shape_Area (selected features) | 13409416.442228 | 22174761.0782468 | 17923143.2021348 | 4635208.85224721 |
| Shape_Area_ (all features) | 2371.65704665466 | 26428935781.0803 | 228674520.370887 | 1891363333.58952 |

Layer Name: pop_T1990



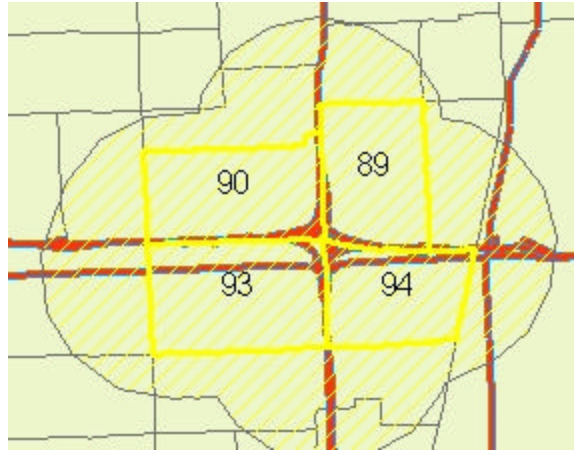
Selected feature values:

| OID | Shape_Area |
|-----|------------------|
| 77 | 21654122.1035421 |
| 78 | 22153250.2113027 |
| 81 | 14425353.2874404 |
| 82 | 13432782.962414 |

Statistical results on the numeral fields of the above table:

| Field Name | Minimum | Maximum | Mean | Standard Deviation |
|-------------------------------|-----------------|------------------|------------------|--------------------|
| Shape_Area(selected features) | 13432782.962414 | 22153250.2113027 | 17916377.1411748 | 4626434.73685868 |
| Shape_Area(all features) | 0 | 26418389799.5361 | 253809986.783011 | 2010456892.18533 |

Layer Name: pop_T2000



Selected feature values:

| OID | Shape_Area |
|-----|------------------|
| 89 | 16882718.6065838 |
| 90 | 18722851.2771107 |
| 93 | 21584740.4105733 |
| 94 | 14796723.4259066 |

Statistical results on the numeral fields of the above table:

| Field Name | Minimum | Maximum | Mean | Standard Deviation |
|--------------------------------------|------------------|------------------|------------------|--------------------|
| Shape_Area (selected features) | 14796723.4259066 | 21584740.4105733 | 17996758.4300436 | 2879938.32521485 |
| Shape_Area (all features) | 10774.21925456 | 26458782646.8306 | 194748185.390581 | 1642050489.89589 |

Appendix IV: Examples of Transland Scenario Implementation

Table IV.1: An Example of Transland Scenario 2

| <i>Scenario 2 example: Where were the areas that experienced greater than 20% land value increases between 1995 and 2000 within a half-mile zone of I-595?</i> | |
|--|--|
| Steps | Transland Classes Related to Each Step |
| 1) Choose scenario 2 | A list of all scenarios |
| 2) Choose TIPs or transportation features | A list of TIP semantic class and a list of all transportation STComposite feature classes included in ArcMap |
| 3) Specify spatial extent and/or attribute query | Selected TIP semantic classes or selected features from transportation STComposite feature classes |
| 4) Specify the time instants or time intervals | Time and Time2Space object classes |
| 5) Generate final display and summary report | Selected features from land use snapshot and STComposite feature classes |

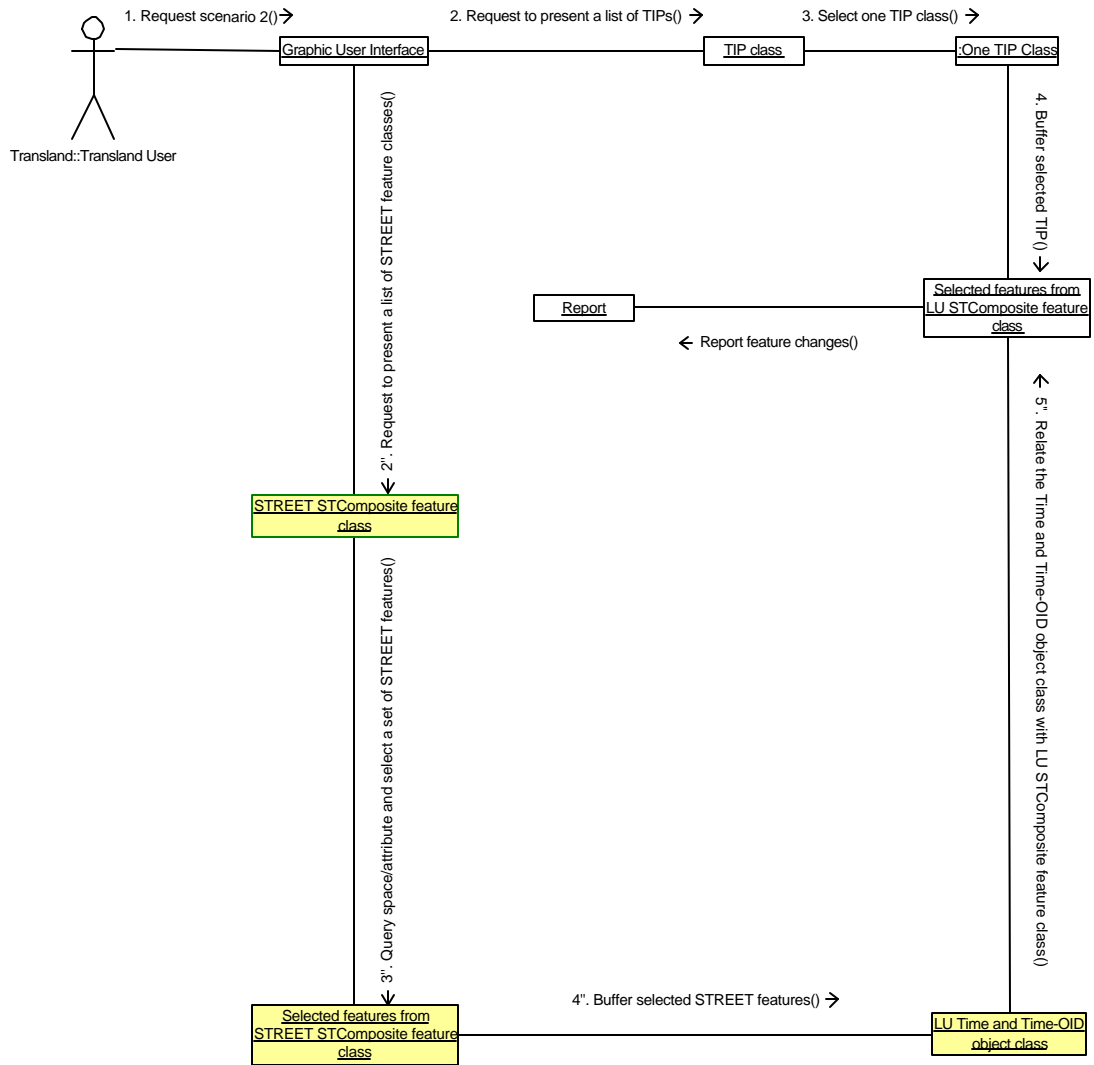


Figure IV.1: A UML Collaboration Diagram for Scenario 2

Table IV.2: An Example of Transland Scenario 3

Scenario 3 example: Where were the vacant land parcels within a 1-mile zone of ongoing transportation projects in 1996?

| Steps | Transland Classes Related to Each Step |
|--|---|
| 1) Choose scenario 3 | A list of all scenarios |
| 2) Specify time instants | Time and Time2Space object classes |
| 3) Specify TIPs or transportation features | A list of TIP semantic class and a list of all transportation STComposite feature classes included in ArcMap |
| 4) Specify spatial extent and/or attribute query | Selected TIP semantic classes or selected features from transportation STComposite feature classes within the temporal constraint specified in step 2 |
| 5) Specify land use data fields to be included in the analysis | Selected land use STComposite and snapshot feature classes within the constraints specified in step 4 |
| 6) Generate final display and summary report | Selected features from land use snapshot and STComposite feature classes |

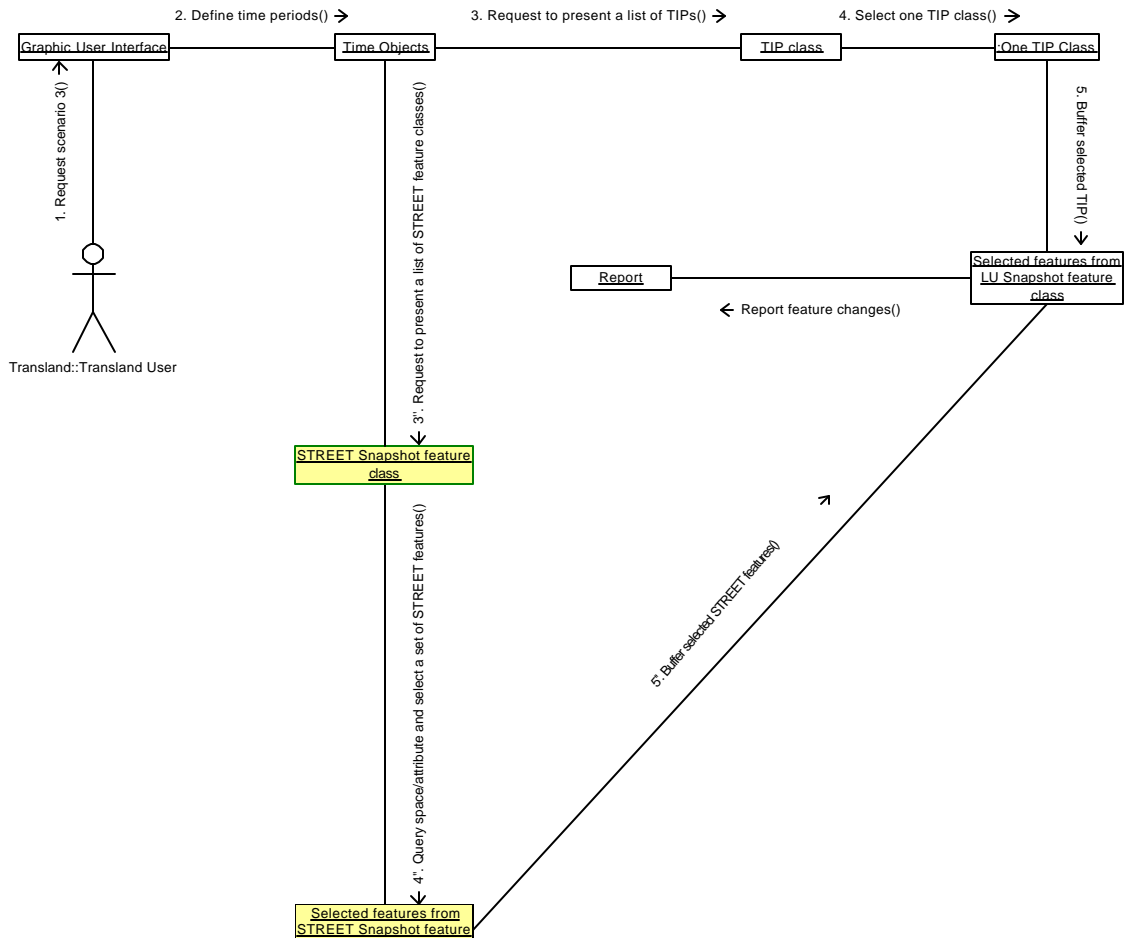


Figure IV.2: A UML Collaboration Diagram for Scenario 3

Table IV.3: An Example of Transland Scenario 4

Scenario 4 example: Which street segments that are adjacent to commercial land use in the study area had a traffic volume/capacity ratio greater than 1 in 1998?

| Steps | Transland Classes Related to Each Step |
|--|--|
| 1) Choose scenario 4 | A list of all scenarios |
| 2) Specify time instants | Time and Time2Space object classes |
| 3) Specify land development semantic objects or land use features | A list of land development semantic class and a list of all land use STComposite feature classes included in ArcMap |
| 4) Specify spatial extent and/or attribute query | Selected land development semantic classes or selected features from land use STComposite feature classes within the temporal constraint specified in step 2 |
| 5) Specify transportation data fields to be included in the analysis | Selected transportation STComposite and snapshot feature classes within the constraints specified in step 4 |
| 6) Generate final display and summary report | Selected features from transportation snapshot and STComposite feature classes |

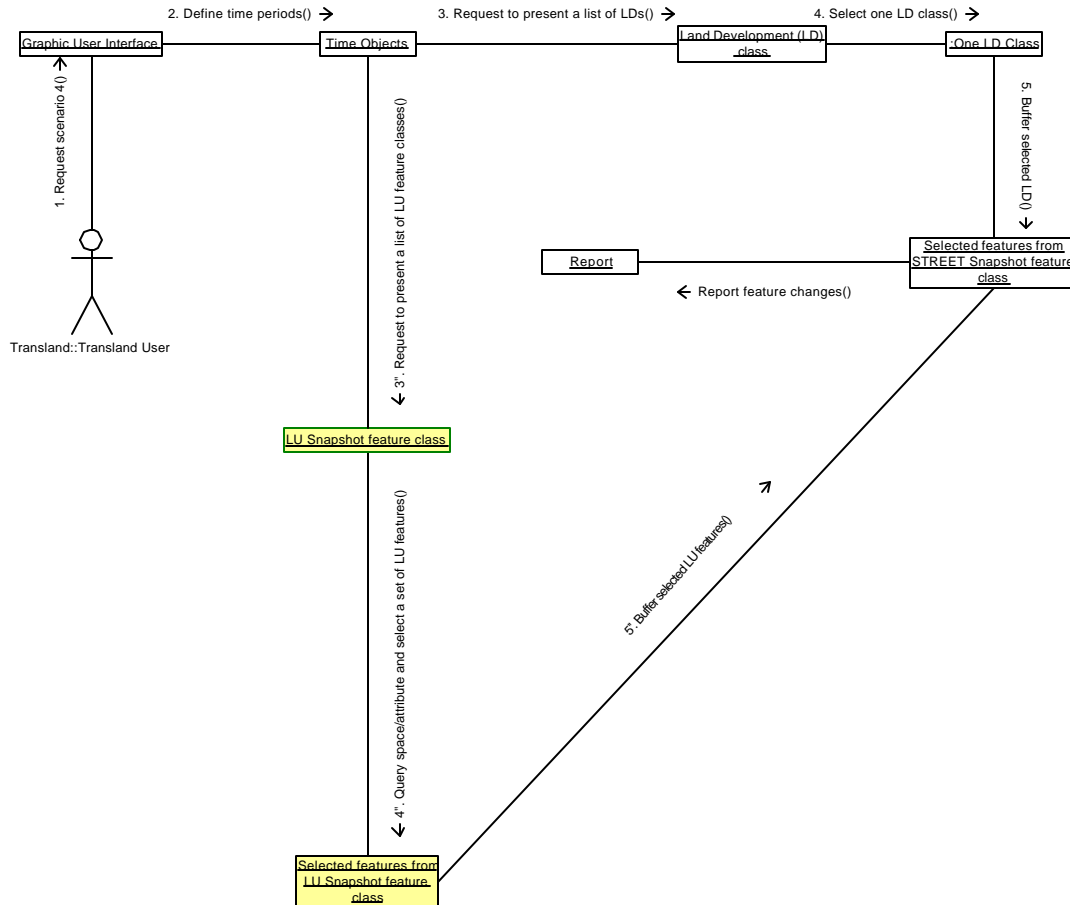


Figure IV.3: A UML Collaboration Diagram for Scenario 4

Table IV.4: An Example of Transland Scenario 5

Scenario 5 example: When did traffic volumes on major streets increase by more than 30% in those traffic analysis zones reaching an employment density of 10,000 per square mile?

| Steps | Transland Classes Related to Each Step |
|--|---|
| 1) Choose scenario 5 | A list of all scenarios |
| 2) Choose land development projects or land use features | A list of land development semantic class and a list of all land use STComposite feature classes included in ArcMap |
| 3) Specify spatial extent and/or attribute query | Selected land development semantic classes or selected features from land use STComposite feature classes |
| 4) Specify land use data fields to be included in the analysis | Transportation STComposite and snapshot feature classes within the constraints specified in step 3 |
| 5) Generate final display and summary report | Transportation snapshot, STComposite, Time and Time2Space classes |

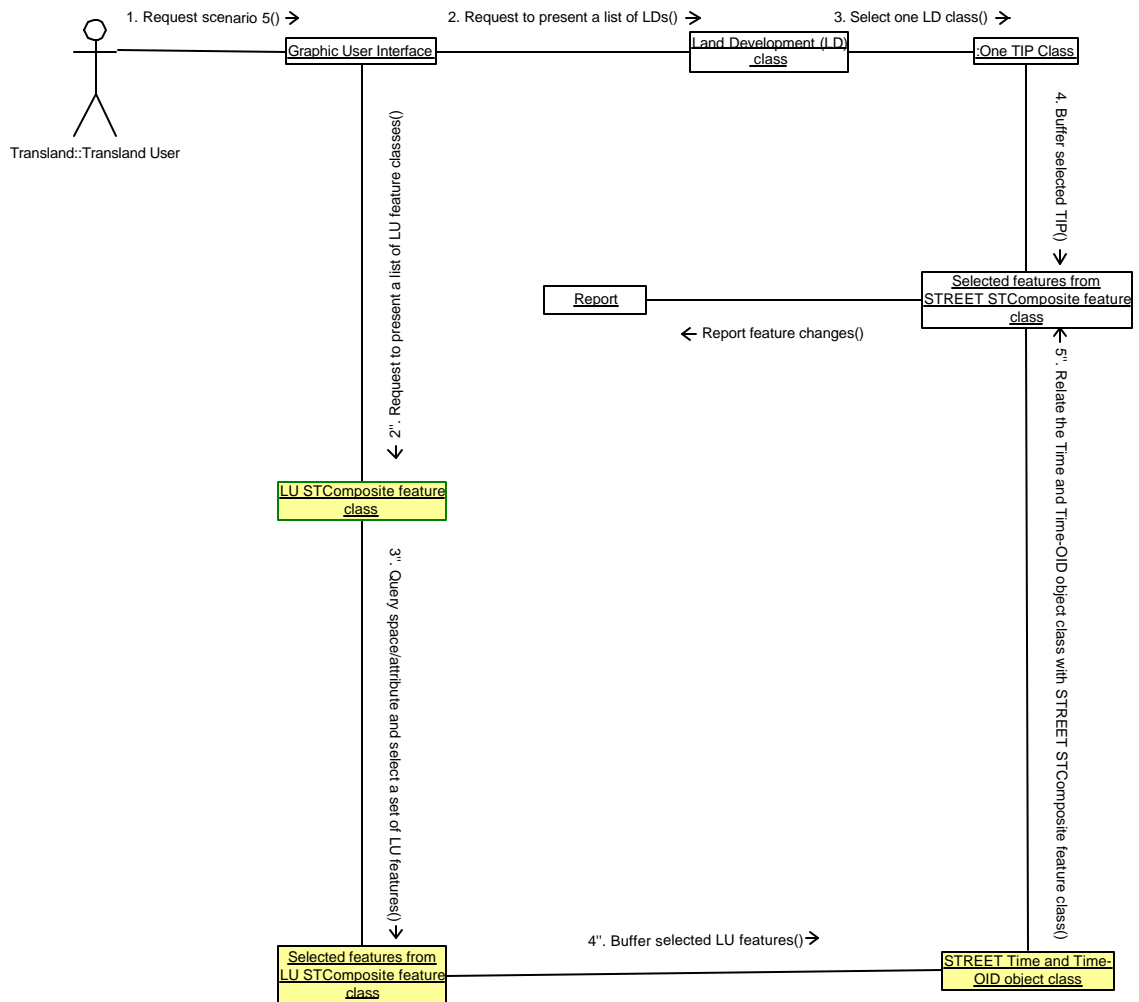


Figure IV.4: A UML Collaboration Diagram for Scenario 5

Table IV.5: An Example of Transland Scenario 6

Scenario 6 example: What were the traffic volumes on major streets in each census tract with an annual population growth rate over 5% from 1990 to 2000?

| Steps | Transland Classes Related to Each Step |
|--|---|
| 1) Choose scenario 6 | A list of all scenarios |
| 2) Choose land development projects or land use features | A list of land development semantic class and a list of all land use STComposite feature classes included in ArcMap |
| 3) Specify spatial extent and/or attribute query | Selected land development semantic classes or selected features from land use STComposite feature classes |
| 4) Specify the time instants or time intervals | Time and Time2Space object classes |
| 5) Generate final display and summary report | Selected features from transportation snapshot and STComposite feature classes |

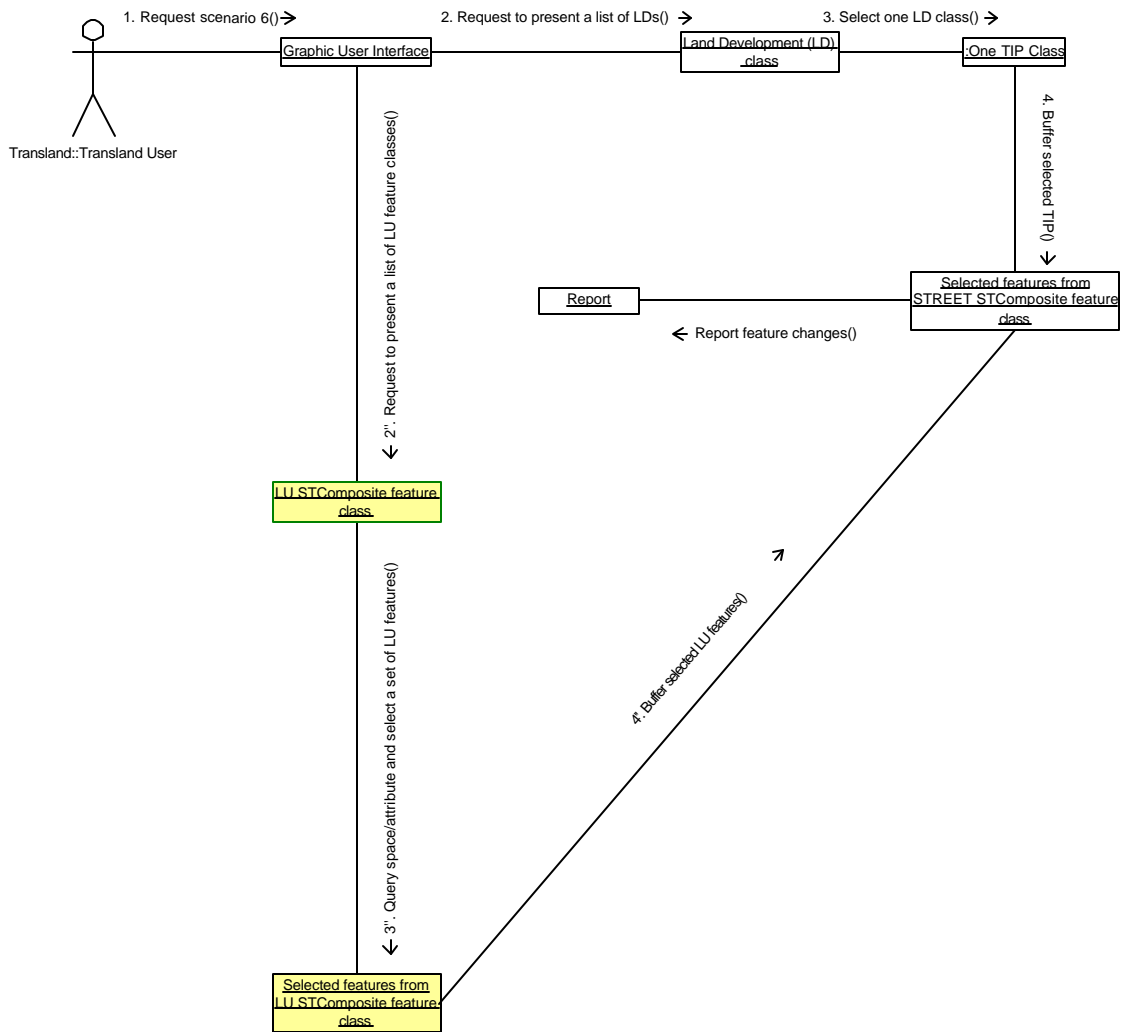


Figure IV.5: A UML Collaboration Diagram for Scenario 6

Appendix V: A README File for Enclosed Source Codes

(included within transland.zip attached for the dissertation)

README.TXT file

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This file updated on Jan. 10, 2003

Transland Prototype Applications
Developed for Exploratory Data Analysis of Land Use-Transportation
Interaction
tested under Windows 2000/NT

1. Requirements
2. Installation
3. Bugs, problems, suggestions
4. Distribution
5. Disclaimer
6. Files on installation disk

1. Requirements:

=====

The following are recommended minimum requirements:

Windows 2000/NT
Microsoft Visual Basic 5.0
ESRI ArcGIS 8.1 Desktop
ESRI ArcObjects 8.1
Microsoft Internet Explorer 5.0 or higher

2. Installation:

=====

Unzip transland.zip, install it to your desired location, and run from there.

3. Bugs, problems, suggestions:

=====

Note that the applications have not yet been tested on all data sets and different hardware platforms.

I welcome feedback on bugs, problems, incompatibilities and any suggestions you may have. Contact the author Xiaohong Xin via email at shaunaxin@hotmail.com

4. Distribution:

=====

The applications may be copied and distributed freely for academic purposes.

5. Disclaimer:

=====

Significant efforts were put into the development and testing of these applications. However, these applications are the first-phase of an ongoing research project. There could be undetected errors in the applications. Users may use these applications at their own risk.

6. Files included in transland.zip:

=====

The following ONE (1) file and NINE (9) folders are included:

| | |
|--------------|--|
| readme.txt | this ASCII file |
| bmp | a folder containing bitmap image icon files, used for icons acting as ArcMap custom tools shown in Figure 5.5 of this dissertation |
| javafile | a folder containing Java class files |
| classmodule | a folder containing Visual Basic class module files |
| module | a folder containing Visual Basic module files |
| animation | a folder containing a Visual Basic project implementing the Transland animation tool window (see Figure 5.6(a)) |
| property | a folder containing a Visual Basic project implementing the Transland property tool window (see Figure 5.6(b)) |
| timestamping | a folder containing a Visual Basic project implementing the Transland time-stamping tool window (see Figure 5.6(c)) |
| stcomposite | a folder containing a Visual Basic project implementing the Transland STComposite tool window (see Figure 5.6(d)) |
| scenario | a folder containing a Visual Basic project implementing the Transland scenario tool window (see Figure 5.6(e)) |

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(end of README.TXT file)

VITA

Xiaohong Xin was born in Urumqi, a capital city of Xinjing Uygur Autonomous Region, P. R. China, on November 4, 1969. She received her bachelor's degree from Lanzhou University, Gansu, P. R. China, in 1991, with a major in Economic Geography and Urban & Regional Planning. She also received her master's degree from Lanzhou University in 1994, with a major in Urban & Regional Planning. After graduating from Lanzhou University, she became an instructor at Lanzhou University to teach Regional Economic Geography and Urban Economics from 1994 to 1995. In 1995, she entered the Department of Geography at the University of Tennessee, Knoxville (UTK) in pursuit of a master's degree and a doctorate with an emphasis in Geographic Information Systems and Transportation Geography. She is a member of the Association of American Geographers (AAG). Her master's thesis was awarded the Best Master Thesis by the AAG Transportation Geography Specialty Group in 2000. In the same year, she also won the second place in the Student Paper Competition of the AAG GIS Specialty Group. Upon a successful defense of her Ph.D. dissertation on November 26, 2002, she will conduct one-year research in the Chinese University of Hong Kong.